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PART I

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STRUCTURAL EVALUATION OF SUPERPLASTIC ALUMINUM

PART I - Mechanical, Corrosion, Metallurgical Data

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AIR FORCE WRIGHT AERONAUTICAL LABORATORIES
AIR FORCE SYSTEMS COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OHIO 45433

NOTICE

This technical report has been reviewed and is approved for publication.

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The mechanical, corrosion, metallurgical and secondary fabricability properties of the superplastically formable Supral alloy were evaluated to assess the amenability of these alloys to standard aircraft practices. Fracture and fatigue properties were evaluated through extensive testing of superplastically formed parts and discs.

The mechanical property test results meet Alcan/Superform claims provided that the microcavitation is restricted to less than three percent of the volume. Research findings show that Supral 100, 150, and 220 are alloys suitable for aircraft use. Testing of shop manufacturing practices and welding techniques indicate that the Supral alloys are comparable to standard U.S. aluminum alloys.

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FOREWORD

This final report Part I documents the technical activities conducted under Contract F33615-83-C-3208, Project Number 2401, from June 1983 through March 1985.

This contract with Fairchild Republic Company is sponsored by the Air Force Wright Aeronautical Laboratories, Flight Dynamics Laboratory, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio. The contract had been monitored by Captain Rodney L. Wilkinson and Lt. Raymond K. Cannon. The current monitor is Lt. David Graves.

The contractor's technical effort is being conducted within the Manufacturing Technology Department, managed by Mr. Alvin Shames. Mr. Julius Stock serves as Program Monitor and Ms. Hadassah C. Lipsius is the Principal Investigator. The following personnel have contributed to this contract: Mr. Walter Trepel, Chief of Manufacturing Technology; Mr. Martin Pollack; Mr. Jimmy Poon; Mr. Theodore Renshaw, Mr. Richard Rupp; and Mr. William Johnson.

TABLE OF CONTENTS

TABLE OF CONTENTS (Cont'd)

LIST OF FIGURES

LIST OF FIGURES (Cont'd.)

LIST OF FIGURES (Cont'd.)

LIST OF TABLES

LIST OF TABLES (Cont'd.)

SECTION I

INTRODUCTION

Rising costs of military hardware and increased emphasis on high durability aircraft structures have challenged the aircraft designer and manufacturing research engineer. This has led to the development of unique manufacturing processes and materials to complement innovative designs. Superplastic forming is an attractive process for aluminum alloys which has potential for reducing cost, decreasing structural weight and improving design efficiency. Advancements in superplastic forming have been concentrated in the United States and Great Britain.

In the United States, research has centered around the 7475 alloy which is processed thermally and mechanically prior to superplastic forming by a patented overaging, warm deformation and recrystallization cycle. The properties of 7475 treated for superplastic forming have been evaluated under a number of DoD contracts, such as F33615-81-C-3227. The material, metallurgical and fabricability properties of superplastic alloys have been well documented in literature. The AIME Proceedings of 1982, "Superplastic Forming of Structural Alloys" by N. E. Paton and C. H. Hamilton, is one of many excellent compendiums on superplastic alloys.

In Great Britain, industrial superplastic forming progressed from the 1960's with architectural panels using non-heat treatable (Supral 5000) to currently used heat treatable alloys such as Supral 100, a clad version Supral 150, and the high strength Supral 220. These alloys which rely on in-process (dynamic) recrystallization to achieve superplasticity have a higher strain rate and lower superplastic forming temperature than the 7475 alloy. The lower superplastic forming temperature of the Suprals permits the use of aluminum tooling rather than ferrous.

There are a number of techniques used in superplastic fabrication, but basically they fall into female and male forming. The female forming technique is used in the United States and the patented male forming in England. Male forming permits deeper parts with more uniform wall thickness than female forming.

This research contract evaluates the mechanical properties, metallurgical characteristics and corrosion resistance of Supral 100, 150 and 220. Information is also included on fracture mechanics and the effects of surface treatments, chem-milling, welding and heat treating. The data generated herein provides information on male formed Supral alloy parts which can be readily compared with other DoD studies of the 7475 alloy.

SECTION II

TASK A - MATERIAL EVALUATION (SUPRAL 100, 150, 220)

2.1 OBJECTIVE

The objective of this task was to evaluate the mechanical, corrosion, fracture mechanics and physical properties of the Supral 100 (2004), 150 (2004 clad) and 220 clad alloys, and to investigate the effect of various standard manufacturing processes on these alloys. The majority of work was performed on the high strength Supral 220 alloy.

2.2 APPROACH

2.2.1 Property Evaluation

Task A provides basic mechanical property, corrosion test, metallographic and physical property data on the high strength Supral 220 (clad) alloy. There are additional test results on the Supral 100 and 150. Table 1 describes the type and number of tests performed.

2.2.2 Structural Component Selection

The T-46A prototype nacelle lip (see Figure 1) was selected for SPF fabrication after a careful review of many parts and consultations with Superform Metals, Ltd., Worcester, United Kingdom.

This part presents a challenge for production by SPF with regard to attaining desired thicknesses in specified areas and achieving low cavitation porosity. The conventional method for fabricating the nacelle lip would be to hydroform and join by fusion welding in a medium strength alloy.

2.2.3 Selection of Test Specimens

In any extensively formed part, thickness will vary across the part. The amount of thinning known as equivalent strain is defined as:

$$\text{Equivalent Strain (\% EQS)} = \left(\frac{\text{Original Thickness}}{\text{Final Thickness}} - 1 \right) \times 100$$

For maximum utilization of material, three strain ranges were tested: low, medium and high.** Superplastically formed discs, of the same lot as the

** High Range = 150-250% EQS
Medium Range = 75-150% EQS
Low Range = 25- 75% EQS

TABLE 1. TEST MATRIX A

Test Procedure Description	Number of Test Specimens		
	Supral 100 Nacelle Lip and Disc Material	Supral 150 Nacelle Lip and Disc Material	Supral 220 Nacelle Lip and Disc Material
Tension; Smooth ($K_T = 1$) Parallel to Strain	9*	9*	35
Tension; Smooth ($K_T = 1$) Perpendicular to Strain	9*	9*	35
Tension; Notched ($K_T = 3$) Parallel to Strain	9*	-	35
Tension; Notched ($K_T = 3$) Perpendicular to Strain	9*	-	35
Tension; Sharp Notched ($K_T = 16$)	9*	-	35
Tension; Smooth -65°F	15	15	
Tension; Notched ($K_T = 3$) -65°F	-	-	-
Tension; Smooth ($K_T = 1$) 210°F	15	15	-
Compression	9*	9*	35
Bearing e/d = 1.5	9*	9*	35
Bearing e/D = 2.0	9*	9*	35
Fatigue; Smooth ($K_T = 1$) Parallel to Strain	-	35*	40
Fatigue; Smooth ($K_T = 1$) Perpendicular to Strain	35	35	
Fatigue; Notched ($K_T = 3$) Parallel to Strain	-	-	40
Stress Corrosion Parallel to Strain	-	-	15
Stress Corrosion Perpendicular to Strain	-	-	15
Cavitation	-	-	35
Hardness	-	-	70
Electrical Conductivity	15	15	
Metallography	15	15	85
Corrosion (Salt Spray)	-	-	15
Crack Propagation Test Specimens Machined by FRC for AFFDL Test	-	-	15
Fatigue Crack Initiation Test Specimens Machined by FRC for AFFDL Test	-	-	15
Tension; Specimens Machined by FRC for AFFDL Test	-	-	15

*Tests independently funded by Fairchild Republic Company

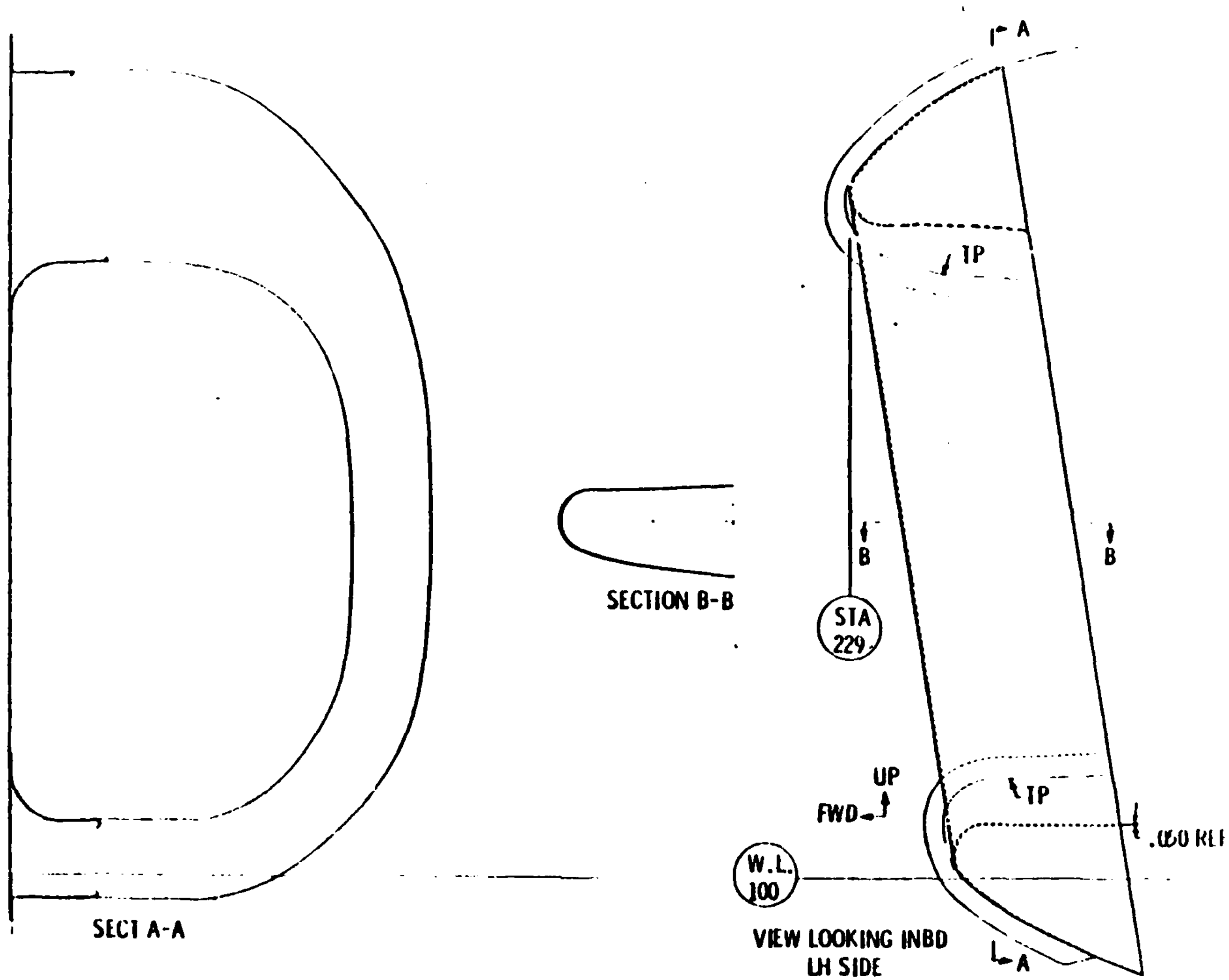

Figure 1. Fairchild Nacelle Lip

part and stretched to the required equivalent strain, were used to supplement the prototype formed parts. The nacelle lip contained very small areas of the high equivalent strain range; therefore, the majority of the test specimens were selected from these discs.

Figure 2 shows the locations of the equivalent strain ranges.

2.2.4 Description of Mechanical and Corrosion Property Tests

The mechanical and corrosion property tests were performed in accordance with ASTM testing standards. Table 2 lists the ASTM standard with the respective test. Unless otherwise noted, the test specimens were prepared from two directions - one parallel and one perpendicular to the major strain.

2.2.4.1 Electroconductivity Tests

Electroconductivity was measured on a NORTEC NDT-5A conductivity tester.

2.2.4.2 Metallography

Optical metallographic examinations were performed to study the microstructural appearance and grain size. A LECO Neophot 21 metallograph was used for all examinations.

2.2.4.3 Cavitation

Microcavitation was determined metallographically to correlate the degree of cavitation with the percent equivalent strain and the mechanical properties. Measurements were made utilizing the linear intercept method.

2.2.5 Tests Performed by AFWAL

Fairchild's Manufacturing Technology Department prepared additional test specimens of clad Supral 220 material for crack propagation, fatigue, tensile and rain erosion testing by AFWAL/FIBE. The test results are incorporated into this report.

2.2.6 Manufacturing Processes

Fairchild evaluated the effect of various standard manufacturing processes and material joining techniques on the Supral alloys. Primarily, manufacturing processing evaluations were performed on the Supral 150 alloy; in some cases, the other Supral alloys were tested. The processes and joining methods, which include ultrasonic and adhesive weldbonding, are described below.

2.2.6.1 Chemical Cleaning

The effects of various standard aircraft cleaning solutions were examined

Figure 2. Nacelle Equivalent Strain Ranges MR-6322

TABLE 2. DESCRIPTION OF TESTING PROCEDURES

Test Description	Method of Testing
Tension; Smooth (K_T = 1) Parallel to Strain	ASTM E8
Tension; Smooth (K_T = 1) Perpendicular to Strain	ASTM E8
Tension; Notched (K_T = 3) Parallel to Strain	ASTM E338
Tension; Notched (K_T = 3) Perpendicular to Strain	ASTM E338
Tension; Sharp Notched (K_T = 16)	ASTM E338
Tension; Smooth (K_T = 1) -65°F	ASTM E231
Tension; Notched (K_T = 3) -65°F	ASTM E231
Tension; Smooth (K_T = 1) 210°F	ASTM E21, E231
Compression	ASTM E9
Bearing e/D = 1.5	ASTM E238
Bearing e/D = 2.0	ASTM E238
Fatigue; Smooth (K_T = 1) Parallel to Strain	ASTM E466
Fatigue; Smooth (K_T = 1) Perpendicular to Strain	ASTM E466
Fatigue, Notched (K_T = 3) Perpendicular to Strain	ASTM E466
Fatigue; Notched (K_T = 3) Parallel to Strain	ASTM E466
Stress Corrosion Parallel to Strain	ASTM G44, G49
Stress Corrosion Perpendicular to Strain	ASTM G44, G49
Hardness	ASTM E18
Electrical Conductivity	FRC Standards
Corrosion (Salt Spray)	ASTM B117, G46

by observing resulting surface conditions and conducting corrosion tests (salt spray) after Alodine and sulphuric acid anodize.

2.2.6.2 Chemical Milling

Chemically milled Supral alloys were evaluated for pitting, corrosion appearance and rating of ease-of-chemical-milling.

2.2.6.3 Spot Welding

A weld schedule which satisfied the requirements of military specification MIL-W-6858C was determined for Supral 150. Lap shear tests were also conducted.

2.2.6.4 Fusion Welding

Supral 150 was evaluated under three conditions:

A. SPF + weld + solution heat treat + age

B. SPF + solution heat treat + age + weld

C. SPF + solution heat + weld + age

These conditions are hereinafter designated as Condition A, B, and C, respectively.

The welds were examined microscopically and transverse tensile tests were conducted.

2.2.6.5 Fastener Allowables

Supral 150 test specimens were evaluated for fastener allowables. Lap joint shear specimens were used to determine the strength of mechanically fastened sheet metal lap joints.

2.2.6.6 Ultrasonic Weldbonding

Lap shear test specimens were prepared using the Supral 220 alloy. Multi-spot single overlap joint panels were prepared, and the joint static strength was established.

2.2.6.7 Adhesive Bonding

Lap shear and wedge crack tests were performed using Forest Product Laboratory (FPL) etch surface preparation and the PABST* treatment.

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* Primary Adhesively Bonded Structure Technology

2.2.6.8 Weldbonding

Lap shear tests were conducted in accordance with Fairchild Republic standard weldbonding procedures. (See Section VI, Reference 2)

2.3 RESULTS

2.3.1 Property Evaluation of Supral 100-T6

2.3.1.1 Smooth (K_T = 1) Tensile Tests - (FRC Funded)

Tensile tests were conducted with specimens from perpendicular and parallel to the strain. The average values are listed in Table 3. There is a small decrease in the yield and ultimate strength in the high EQS range. The drop in properties in the high EQS range is more pronounced in the percent elongation. It is assumed that the cavitation which is greater in the high EQS range is the cause of the decrease in properties. The differences between the results of the perpendicular and parallel to the strain are negligible and therefore the third condition listed in Table 3 statistically combines the results of the perpendicular tests and parallel tests. This calculation has been performed in the majority of test results tabulated in this report.

2.3.1.2 Notched (K_T = 3) Tensile Tests - (FRC Funded)

Perpendicular and parallel to strain tensile specimens were tested. The results averaged in Table 4 show similar results in the low and medium EQS range. There is a very slight decrease in notched strength in the high EQS range which is more pronounced in the parallel to strain specimens. However, only a small number of specimens were tested and a larger test sample would be required to verify a difference between the two directions.

2.3.1.3 Sharp Notched (K_T = 16) Tensile Tests - (FRC Funded)

Tensile tests were conducted on perpendicular and parallel sharp notched test specimens at three different equivalent strain levels. The results are listed in Table 5. Unlike the previous test results reported, the individual test results are listed. The limited testing was performed in order to obtain a general idea of the properties. The notched strength does not vary with respect to direction nor EQS range.

2.3.1.4 Elevated Temperature Tensile Tests

Smooth (K_T = 1) tensile tests were conducted at a temperature of 210°F. The test results which are the average values of 15 specimens (see Table 1) are listed in Table 6. Figure 3 demonstrates the relationship between the tensile properties and the equivalent strain. Perpendicular and parallel to strain tests yielded comparable results. This is also true for the majority of test data reported herein. At the high equivalent strain range the properties decrease, because microcavitation detrimentally affects the tensile properties. The decrease in properties is more gradual for yield strength and ultimate strength than it is for the elongation, which drops suddenly.

TABLE 3. AVERAGE TENSILE PROPERTIES AT $K_T = 1$
SUPRAL 100 - T6

Condition	EQS Range	Fty, Ksi		Ftu, Ksi		Elong. % in 2"		E Modulus 10^6 psi	
		$\bar{X}$	σ_{n-1}	$\bar{X}$	σ_{n-1}	$\bar{X}$	σ_{n-1}	$\bar{X}$	σ_{n-1}
Parallel to Strain	Low	44.1	0.71	59.3	0.28	12.5	0.71	11.3	0.08
	Medium	44.2	0.37	59.1	0.77	10.7	1.18	11.0	0.49
	High	42.4	0.37	56.8	2.22	7.7	2.90	10.7	0.66
Perpendicular to Strain	Low	45.1	0.38	61.4	1.22	11.7	0.24	10.7	0.33
	Medium	46.7	0.09	63.0	1.20	9.3	0.62	10.6	0.14
	High	43.8	1.36	55.3	3.90	5.1	1.20	10.3	0.28
Perpendicular and Parallel to Strain	Low	44.6	0.74	60.4	1.40	12.1	0.67	11.0	0.37
	Medium	45.5	1.30	61.1	2.20	10.0	1.20	10.8	0.41
	High	43.1	1.20	56.0	3.30	6.4	2.60	10.5	0.50

TABLE 4. NOTCHED TENSILE PROPERTIES AT $K_T = 3$
SUPRAL 100 - T6

Condition	EQS Range	NTS, Ksi		NTS/Fty	NTS/Ftu
		$\bar{X}$	σ_{n-1}		
Parallel to Strain	Low	48.7	0.82	1.104	0.821
	Medium	50.6	0.49	1.144	0.856
	High	44.3	2.39	1.045	0.780
Perpendicular to Strain	Low	51.6	0.16	1.144	0.840
	Medium	49.5	4.38	1.060	0.786
	High	47.6	2.95	1.087	0.861
Perpendicular and Parallel to Strain	Low	50.1	1.60	1.123	0.829
	Medium	50.1	3.17	1.101	0.820
	High	46.0	3.13	1.067	0.821

TABLE 5. SHARP NOTCHED TENSILE PROPERTIES AT K_T = 16
SUPRAL 100-T6

Specimen No.	Condition (to Strain)	EQS Range	NTS, Ksi	NTS/Fty	NTS/Ftu
1	Parallel	Low	48.3	1.095	0.833
2	Perpendicular	Low	49.2	1.091	0.801
3	Perpendicular	Low	50.6	1.122	0.824
4	Parallel	Medium	48.7	1.102	0.824
5	Parallel	Medium	47.8	1.081	0.809
6	Perpendicular	Medium	49.2	1.054	0.781
7	Parallel	High	47.0	1.108	0.827
8	Perpendicular	High	49.6	1.132	0.897
9	Perpendicular	High	51.8	1.183	0.937

TABLE 6. AVERAGE TENSILE PROPERTIES AT T= + 210°F WITH K_T = 1
SUPRAL 100-T6

Condition	EQS Range	Fty, Ksi		Ftu, Ksi		Elongation % in 2"		E Modulus 10^6 psi	
		$\bar{X}$	σ_{n-1}	$\bar{X}$	σ_{n-1}	$\bar{X}$	σ_{n-1}	$\bar{X}$	σ_{n-1}
Parallel to Strain	Low	41.3	0.50	53.5	0.10	15.5	1.80	8.8	0.21
	Medium	39.0	2.32	50.8	2.94	13.0	1.00	9.3	0.99
	High	35.8	2.40	45.0	2.74	6.3	0.58	8.3	0
Perpendicular to Strain	Low	43.9	0.85	56.8	0.78	13.0	0	9.0	0.71
	Medium	41.8	1.77	55.4	2.40	12.8	2.47	9.3	0.99
	High	36.2	4.53	43.9	7.50	4.0	1.40	11.5	0
Perpendicular and Parallel to Strain	Low	42.3	1.40	54.6	1.60	14.5	1.70	8.9	0.40
	Medium	40.1	2.20	52.5	3.10	12.9	1.30	9.3	0.70
	High	35.9	2.50	44.6	3.80	5.4	1.40	9.4	1.50

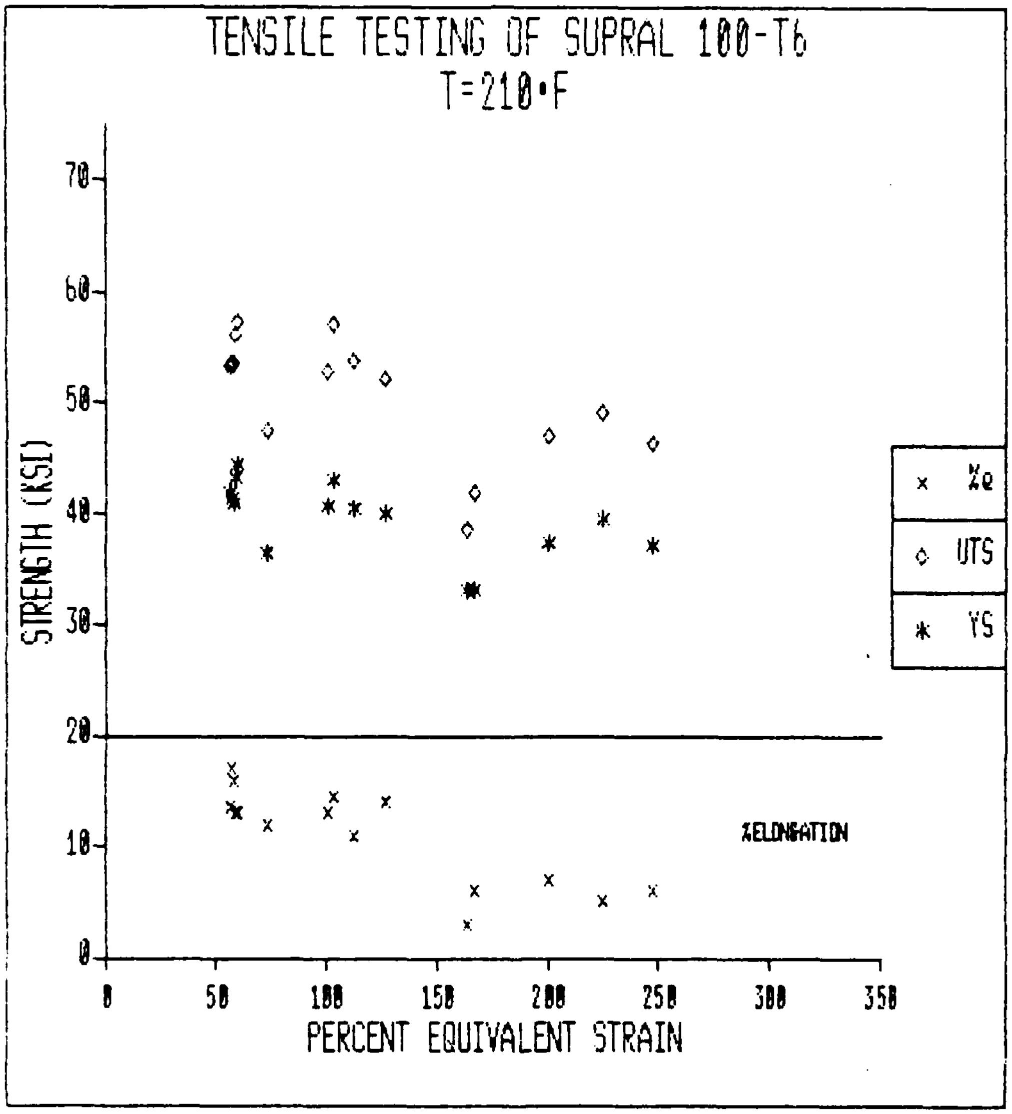


Figure 3. Tensile Properties of Supral 100 at 210^{O}F versus EQS
(Each Point Denotes a Test Result)

2.3.1.5 Subzero Temperature Tensile Tests

Smooth ($K_T = 1$) tensile tests were performed at a temperature of -65°F. The test results which are average values of 15 specimens are listed in Table 7 and plotted against equivalent strain in Figure 4. The yield and ultimate tensile strength are not lower in the perpendicular high equivalent strain range as noted at T = 210°F. The percent elongation, however, does follow the pattern of the tensile tests at 210°F by decreasing in the high EQS range.

2.3.1.6 Compression Tests - (FRC Funded)

The compression test results do not differ in respect to strain direction or EQS range. Cavitation does not appear to have an effect on the compression strength. The individual test results are listed in Table 8.

2.3.1.7 Bearing Tests - e/D = 1.5 - (FRC Funded)

Bearing test results are listed in Table 9. The ultimate strength decreases approximately 10 percent from the low to the medium EQS range and approximately 20 percent from the medium to the high EQS range. Some of the bearing test results were irregular and therefore we have posed several questions on bearing testing of Supral alloys to Superform/Alcan.

2.3.1.8 Bearing Tests - e/D = 2.0 - (FRC Funded)

The test results in Table 10 indicate a decrease in properties as the percent EQS is increased. As mentioned above, several of the results are irregular and we have suggested to Superform/Alcan to research this area further.

2.3.1.9 Fatigue Tests - Perpendicular to Strain

Smooth ($K_T = 1$) axial stress fatigue tests were conducted. The data are presented in the S-N curve in Figure 5. The low-and medium-range EQS curves are very similar. The high-range EQS curve, however, is noticeably lower than the medium-and low-range curves.

2.3.1.10 Electroconductivity

Electroconductivity measurements were made on heat treated (T6) Supral 100 discs and lips. Table 11 shows that the percent IACS (International Annealed Copper Standard) does not vary as the equivalent strain is increased.

2.3.1.11 Metallography

Superplastically formed discs were bisected and five metallographic specimens were cut out along the diameter. The respective equivalent strains were recorded and average grain diameters were calculated (Table 12). Photomicrographs of Keller's reagent etched fine grain samples are shown in Figures 6 and 7. The dark spots seen in the photomicrograph are $CuAl_2$ precipitants.

TABLE 7. AVERAGE TENSILE PROPERTIES AT $T=-65^{o}F$ WITH $K_T=1$

SUPRAL 100-T6

Condition	EQS Range	Fty, Ksi		Ftu, Ksi		Elongation in 2"		E Modulus 10^6 psi	
		$\overline{X}$	σ_{n-1}	$\overline{X}$	σ_{n-1}	$\overline{X}$	σ_{n-1}	$\overline{X}$	σ_{n-1}
Parallel to Strain	Low	46.2	4.10	61.9	0.92	12.5	2.12	10.7	0.35
	Medium	44.0	1.34	58.8	3.32	11.5	3.54	*	-
	High	37.5	1.77	51.7	4.60	7.8	0.35	10.0	-
Perpendicular to Strain	Low	45.6	2.40	62.3	3.08	10.8	2.93	10.8	1.50
	Medium	47.3	1.30	61.5	3.07	7.3	3.40	*	-
	High	50.2	1.14	62.5	2.54	4.3	2.25	*	-
Perpendicular and Parallel to Strain	Low	45.8	2.68	62.1	2.01	11.5	2.50	10.8	1.08
	Medium	46.0	2.16	60.4	3.08	9.0	3.76	*	-
	High	45.1	7.10	58.2	6.62	5.7	2.46	10	-

* Data unavailable

TABLE 8. COMPRESSION STRENGTH -

SUPRAL 100 - T6

Specimen No.	Condition (to Strain)	EQS Range	Yield Strength Fcy, Ksi	Modulus 10^6 psi
1	Parallel	Low	55.4	11.4
2	Parallel	Low	58.1	11.7
3	Perpendicular	Low	61.7	12.1
4	Parallel	Medium	57.8	12.2
5	Perpendicular	Medium	59.1	11.9
6	Perpendicular	Medium	58.7	10.3
7	Parallel	High	56.9	10.3
8	Perpendicular	High	58.5	11.1
9	Perpendicular	High	61.8	*

* Data Unavailable

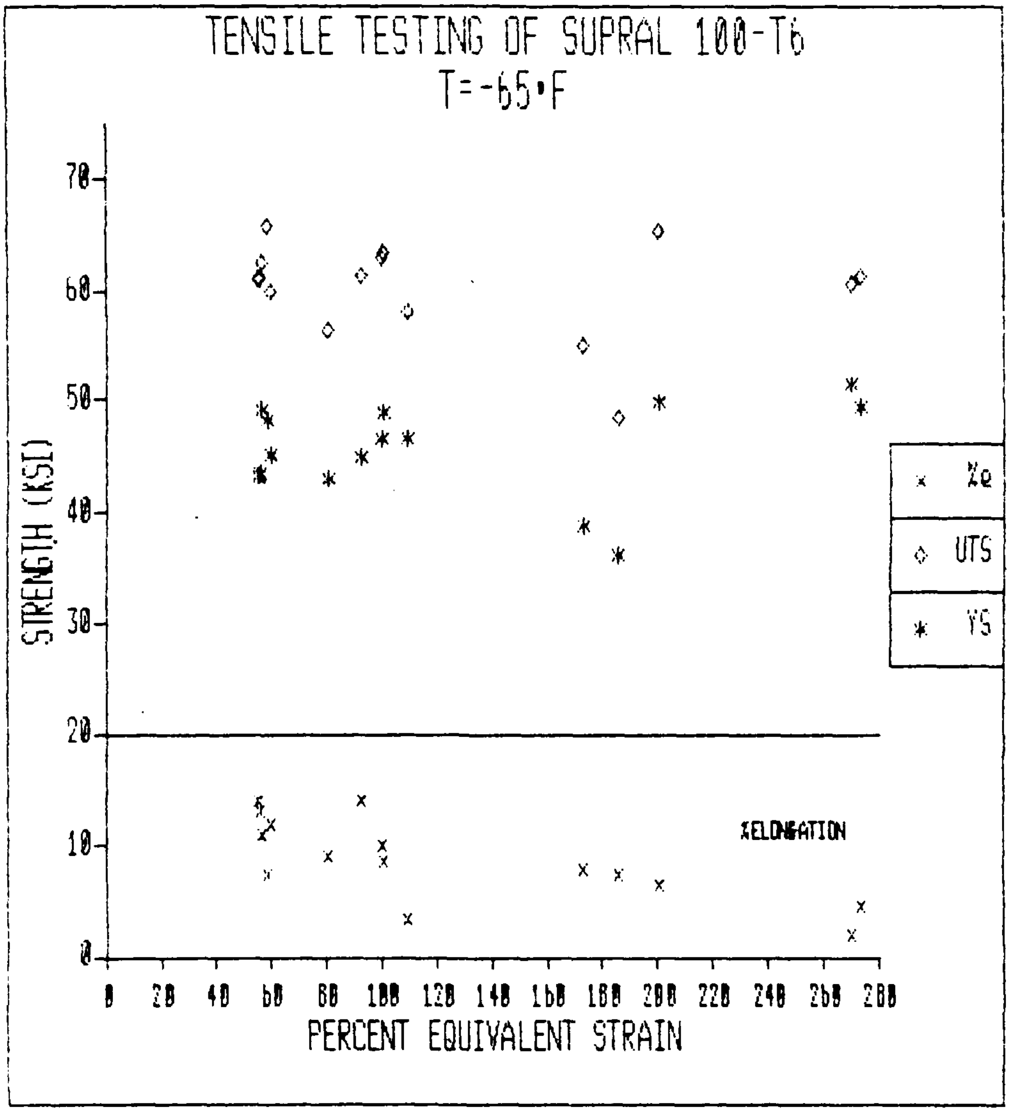


Figure 4. Tensile Properties of Supral 100 at -65°F versus EQS
(Each Point Denotes a Test Result)

TABLE 9. BEARING STRENGTH PROPERTIES (e/D=1.5)

SUPRAL 100-T6

Specimen No.	Condition (to Strain)	EQS Range	Bearing Yield Strength Fbry, Ksi	Bearing Ultimate Strength Fbru, Ksi
1	Parallel	Low	63.3	96.9
2	Perpendicular	Low	62.9	92.8
3	Perpendicular	Low	61.2	93.0
4	Parallel	Medium	62.3	81.6
5	Perpendicular	Medium	64.2	88.8
6	Perpendicular	Medium	56.9	85.9
7	Parallel	High	50.8	69.9
8	Perpendicular	High	57.8	68.9
9	Perpendicular	High	65.4	68.1

TABLE 10. BEARING STRENGTH PROPERTIES (e/D=2.0)

SUPRAL 100-T6

Specimen No.	Condition (to Strain)	EQS Range	Bearing Yield Strength Fbry, Ksi	Bearing Ultimate Strength Fbru, Ksi
1	Parallel	Low	67.6	120.0
2	Parallel	Low	73.0	119.0
3	Perpendicular	Low	71.0	117.0
4	Parallel	Medium	72.2	86.6
5	Parallel	Medium	61.3	74.6
6	Perpendicular	Medium	70.3	88.2
7	Parallel	High	70.7	80.7
8	Perpendicular	High	68.6	74.0
9	Perpendicular	High	49.8	61.2

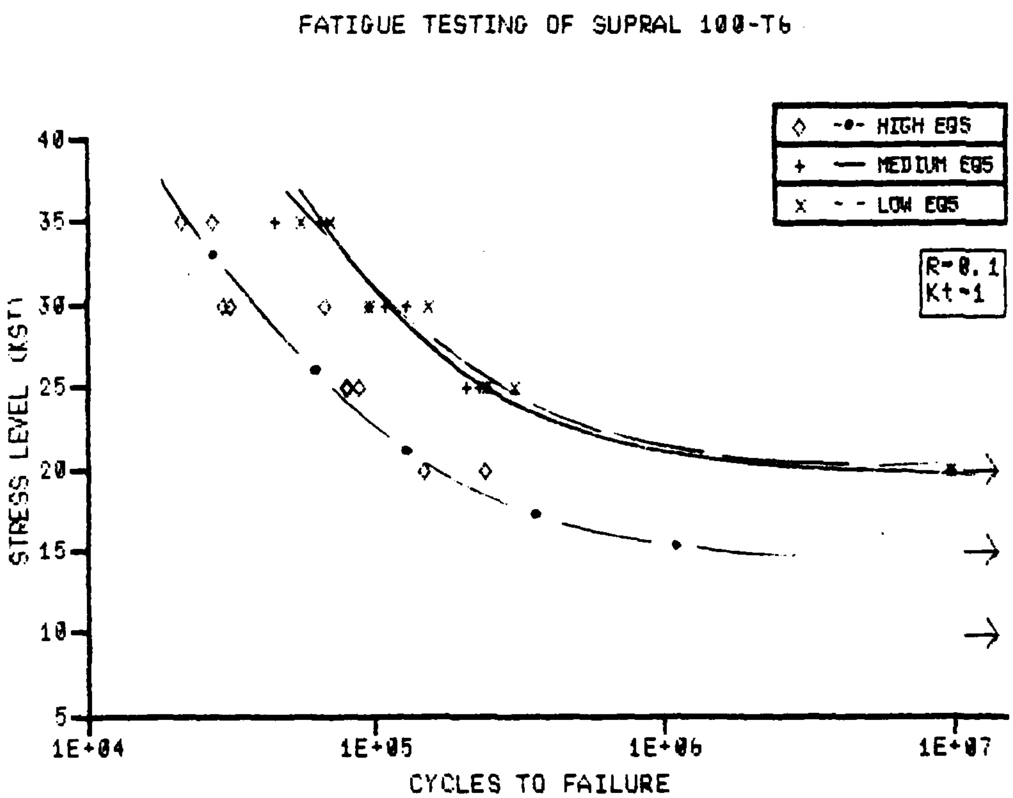


Figure 5. Axial Fatigue Properties of Smooth Specimens - Supral 100-T6

TABLE 11. ELECTROCONDUCTIVITY MEASUREMENTS OF SUPRAL ALLOYS
(% IACS)

CONDITION: HEAT TREATED (T6) DISCS AND NACELLE LIPS

EQS	Alloy			
	Supral 100	Supral 150	Supral 220 Clad	Supral 220 Bare
Low 25-75%	37.5-41.0	38.5-44.5	43.5-45.0	39.5-41.5
Medium 75-150%	39.0-41.5	40.5-43.0	42.0-45.0	42.0-43.5
High 150-250%	35.5-42.0	37.5-42.0	37.0-42.0	*

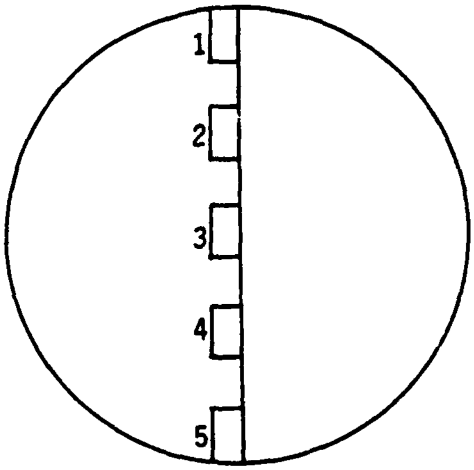
*Data not available at this time

Heat Treatments

Supral 100 and Supral 150 - 530°C for 30 minutes, quench into 30-35% quendilia (glycol), age for 10.5 hours at 177°C, air cool.

Supral 220 - 523°C for 60 minutes, quench into 30-35% quendilia (glycol), age for 8 hours at 190°C, air cool.

TABLE 12. GRAIN SIZE MEASUREMENTS - SUPRAL 100-T6



Position Number	% Equivalent Strain	Average Grain Diameter Microns
Disk 1 (SP2238-32/34)		
1	51.9	4.4-4.7
2	59.9	4.4-4.7
3	61.2	5.0-5.6
4	65.6	4.5-4.7
5	56.4	4.5-4.7
Disk 2 (SP2238-20/34)		
1	109.5	4.6-5.2
2	119.4	5.2-5.6
3	119.4	4.8-5.6
4	99.5	5.0-5.6
5	94.6	5.0-5.6
Disk 3 (SP2238-8/34)		
1	156.5	3.75-4.2
2	197.0	5.0 -5.6
3	245.0	4.4 -5.0
4	216.0	4.3 -4.8
5	153.2	3.75-4.2

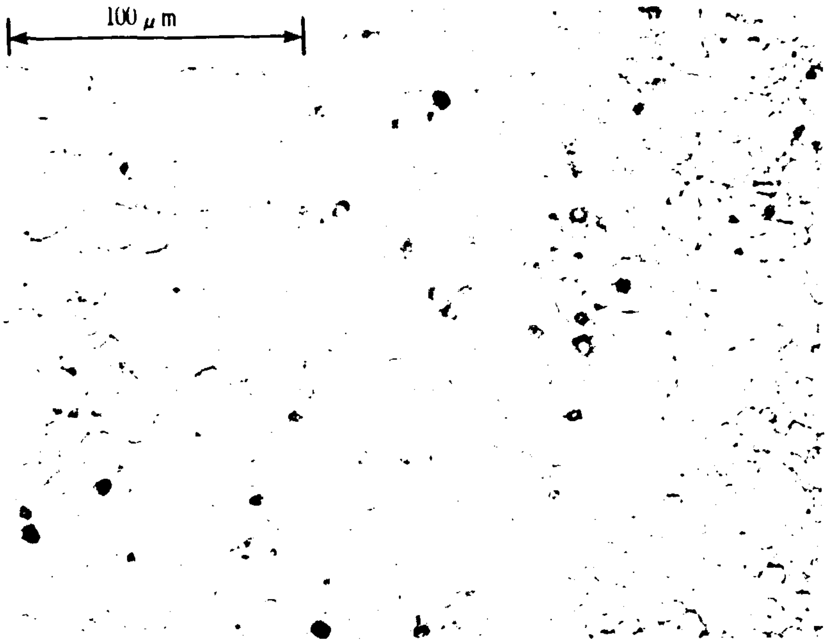


Figure 6. Photomicrograph of Etched Supral 100 - Disk SP2238-32/34 - Position 2 (400X)

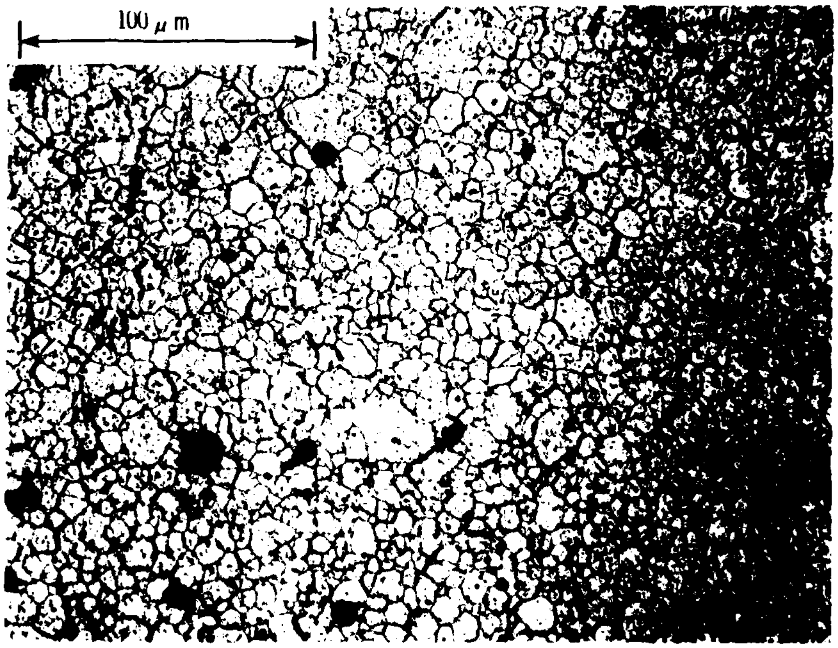


Figure 7. Photomicrograph of Etched Supral 100 - Disk SP2238-20/34 - Position 2 (400X)

2.3.2 Property Evaluation of Supral 150 - T6

2.3.2.1 Smooth (K_T = 1) Tensile Tests - (FRC Funded)

Tensile tests were conducted on smooth tensile specimens. The results in Table 13, listed as average values, indicate a decrease in properties in the high equivalent strain range. This is quite noticeable in the percent elongation.

2.3.2.2 Elevated Temperature Tensile Tests

Smooth (K_T = 1) tensile tests were conducted at a temperature of 210^{o}F. The test results which are average values are listed in Table 14. Figure 8 again demonstrates the relationship between the tensile properties and the equivalent strain. The properties, especially ductility, decrease rapidly as they reach the high EQS range.

2.3.2.3 Subzero Temperature Tensile Tests

Smooth (K_T = 1) tensile tests were performed at a temperature of -65^{o}F. The test results which are average values are listed in Table 15 and plotted versus equivalent strain in Figure 9. As noted at T=210^{o}F, the tensile properties decreased as they reached the high equivalent strain region.

2.3.2.4 Compression Tests (FRC Funded)

The compression test results listed in Table 16 show a slight increase in properties from the low to medium equivalent strain range. The low and high EQS large results are similar in value. Some of the results in the same EQS range differ greatly. The reason for this deviation needs to be investigated further.

2.3.2.5 Bearing Tests - e/D = 1.5 (FRC Funded)

Bearing test (e/D = 1.5) results are listed in Table 17. The results show a great variation in the same strain level. The Supral 150 results are significantly lower than its bare Supral 100 alloy. Further investigation and a larger test set are required to explain the variations.

2.3.2.6 Bearing Tests - e/D = 2.0 (FRC Funded)

Bearing test (e/D = 2.0) results are listed in Table 18. The test sample set is too small and the results vary too greatly to confirm trends in the test results. Further investigation is required to explain the difficulties in bearing testing of the Supral alloys.

2.3.2.7 Fatigue Tests - Perpendicular to Strain

Smooth (K_T = 1) axial stress fatigue tests were conducted. The data are presented in the S-N curve in Figure 10. Unlike the Supral 100, there is no distinction between the high, medium and low EQS range in the clad

TABLE 13. AVERAGE TENSILE PROPERTIES AT K_T=1

SUPRAL 150-T6

Condition	EQS Range	Fty, Ksi		Ftu, Ksi		Elong.% in 2"		E Modulus 10^6 psi	
		$\bar{X}$	σ_{n-1}	$\bar{X}$	σ_{n-1}	$\bar{X}$	σ_{n-1}	$\bar{X}$	σ_{n-1}
Parallel to Strain	Low	42.6	0.70	57.6	1.95	11.0	0.50	10.3	0.58
	Medium	39.5	1.00	52.8	1.72	8.5	0.87	9.7	1.53
	High	36.9	1.13	45.8	5.52	5.3	3.18	9.1	0.40
	High	-	-	33.3*	-	1.1*	-	8.7*	-
Perpendicular to Strain	Low	42.9	1.19	57.0	1.78	8.2	0.58	10.5	0.45
	Medium	41.3	1.01	54.5	1.64	8.0	1.32	10.3	0.58
	High	38.2	0.53	44.5	2.82	2.7	1.26	8.5	0.42
Perpendicular and Parallel to Strain	Low	42.7	0.95	57.3	1.69	9.6	1.62	10.4	0.47
	Medium	40.4	1.41	53.6	1.78	8.3	1.04	10.0	1.10
	High	37.7	0.98	45.0	3.48	3.7	2.31	8.8	0.55

*One sample failed prior to 0.02% offset yield.

TABLE 14. AVERAGE TENSILE PROPERTIES AT T=210°F (K_T=1)

SUPRAL 150-T6

Condition	EQS Range	Fty, Ksi		Ftu, Ksi		Elongation % in 2"		E Modulus 10^6 psi	
		$\bar{X}$	σ_{n-1}	$\bar{X}$	σ_{n-1}	$\bar{X}$	σ_{n-1}	$\bar{X}$	σ_{n-1}
Parallel to Strain	Low	40.2	0.65	52.9	0.42	10.4	1.63	10.4	0.12
	Medium	39.1	0.71	51.1	1.91	9.7	-	10.8	-
	High	35.6	2.33	43.5	2.62	2.8	0.35	8.7	0.07
Perpendicular to Strain	Low	47.1	11.17	54.4	2.69	9.3	0.14	10.5	-
	Medium	39.5	3.55	51.9	2.09	7.9	2.77	10.7	-
	High	35.1	0.70	39.6	4.17	1.7	0.58	*	
Perpendicular and Parallel to Strain	Low	42.9	6.77	53.5	1.61	9.8	1.12	10.4	0.12
	Medium	39.3	2.55	51.6	1.80	8.3	2.44	10.8	0.07
	High	35.3	1.29	41.1	3.87	2.1	0.75		

* Data unavailable

TABLE 15. AVERAGE TENSILE PROPERTIES AT T=-65°F (K_T-1)

SUPRAL 150-T6

Condition	EQS Range	Fty, Ksi		Ftu, Ksi		Elongation % in 2"		E Modulus 10^6 psi	
		$\bar{X}$	σ_{n-1}	$\bar{X}$	σ_{n-1}	$\bar{X}$	σ_{n-1}	$\bar{X}$	σ_{n-1}
Parallel to Strain	Low	39.9	2.08	57.3	1.21	12.3	1.67	11.0	-
	Medium	43.6	0.84	57.1	0.57	10.2	-	10.9	-
	High	35.9	5.02	42.6	7.00	3.0	0	9.4	-
Perpendicular to Strain	Low	42.9	2.19	56.8	2.26	8.6	1.11	10.8	-
	Medium	41.1	1.60	53.5	4.00	7.1	2.19	11.1	-
	High	37.9	0.49	45.2	1.48	2.3	0.35	*	-
Perpendicular and Parallel to Strain	Low	40.9	2.32	57.1	1.44	10.8	2.38	10.9	0.14
	Medium	42.1	1.81	54.9	3.46	8.1	2.39	11.0	0.14
	High	36.9	3.13	43.9	4.4	2.6	0.48		-

* Data unavailable

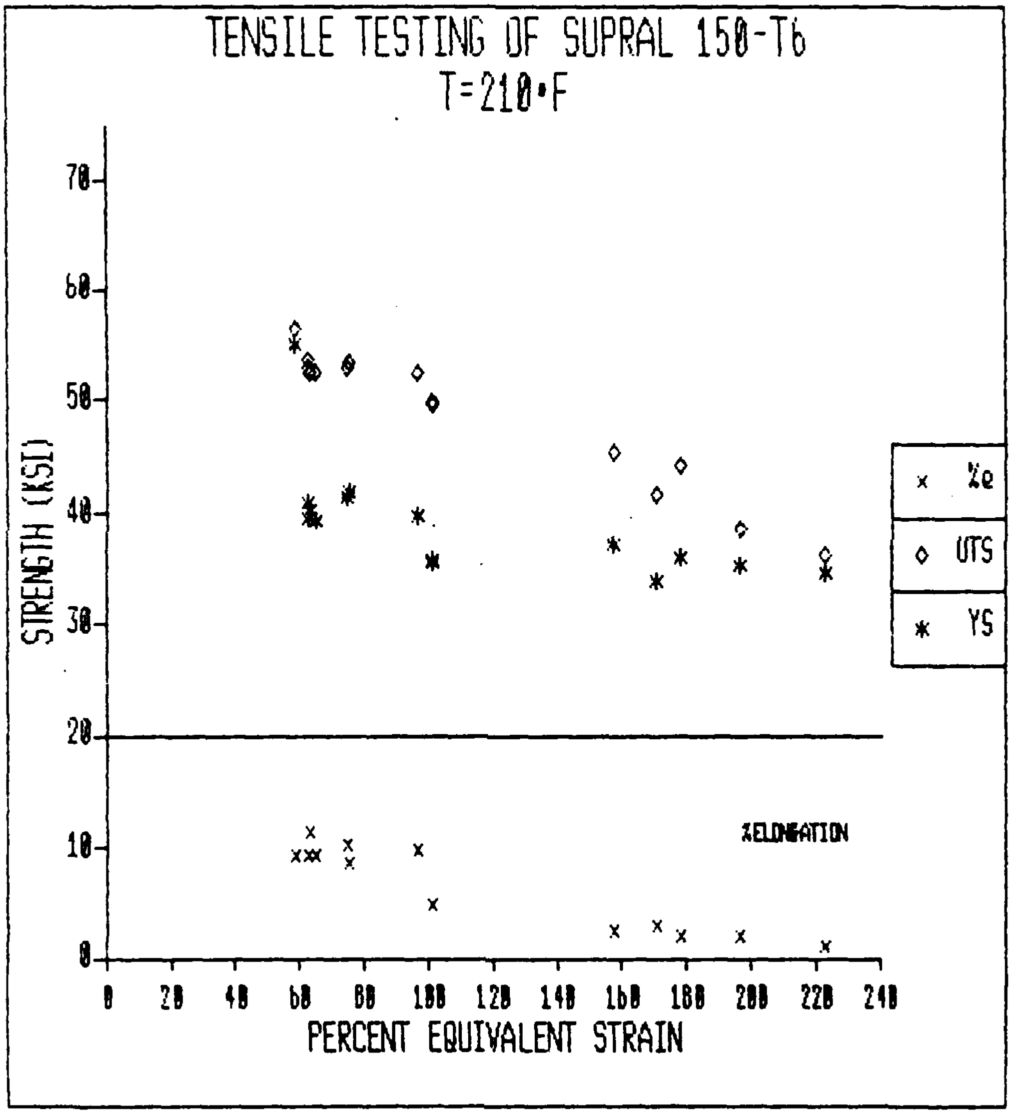


Figure 8. Tensile Properties of Supral 150 at 210^{O}F versus EQS
(Each Point Denotes a Test Result)

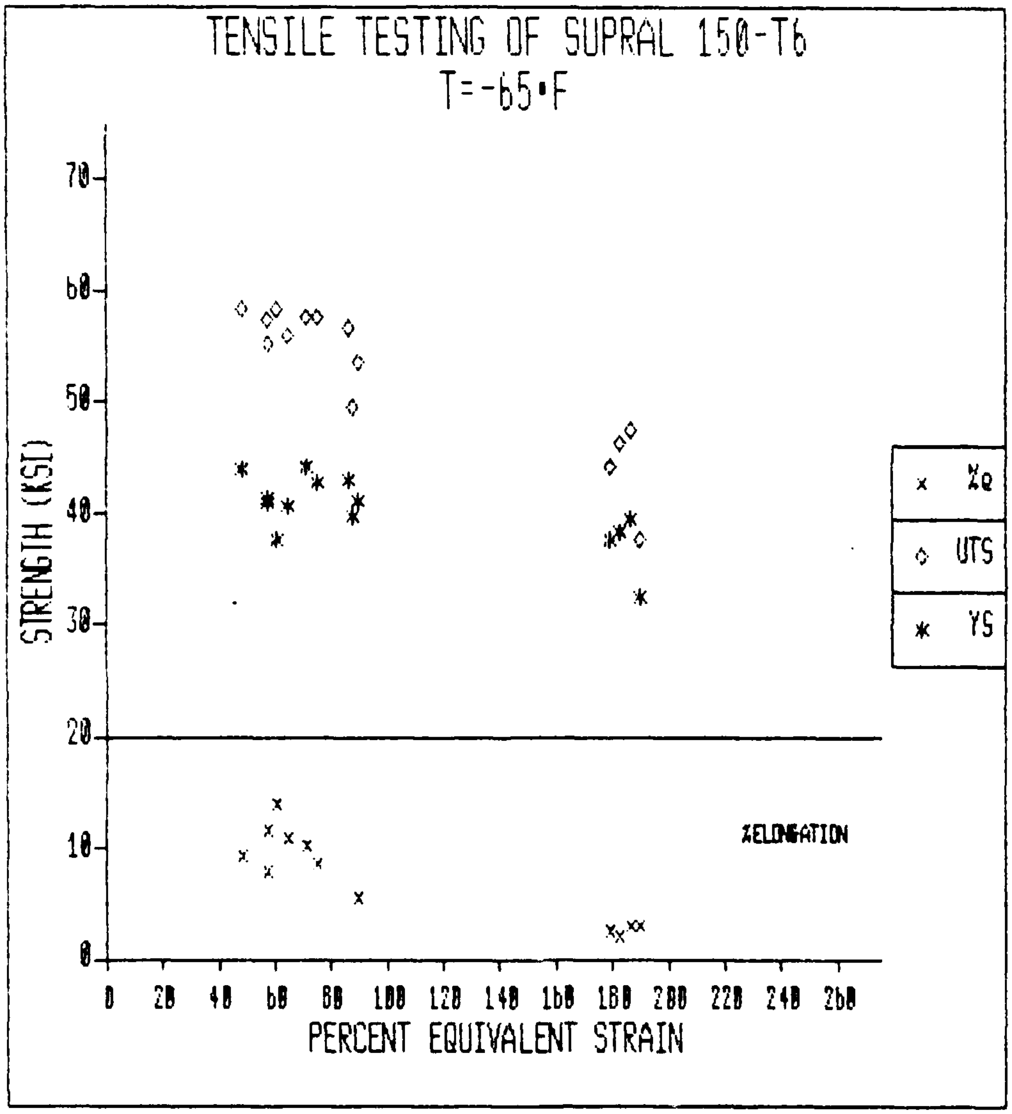


Figure 9. Tensile Properties of Supral 150 at -65°F versus EQS (Each Point Denotes a Test Result)

TABLE 16. COMPRESSIVE STRENGTH

SUPRAL 150-T6

Specimen No.	Condition (to Strain)	EQS Range	Yield Strength Fcy, Ksi	Modulus 10^6 psi
1	Parallel	Low	46.8	9.4
2	Perpendicular	Low	51.3	10.0
3	Perpendicular	Low	48.3	9.6
4	Parallel	Medium	52.3	9.5
5	Parallel	Medium	57.9	12.4
6	Perpendicular	Medium	48.2	9.1
7	Parallel	High	46.5	9.4
8	Parallel	High	56.9	11.8
9	Perpendicular	High	46.5	9.4

TABLE 17. BEARING STRENGTH PROPERTIES (e/D=1.5)

SUPRAL 150-T6

Specimen No.	Condition (to Strain)	EQS Range	Bearing Yield Strength Fbry, Ksi	Bearing Ultimate Strength Fbru, Ksi
1	Parallel	Low	26.4	60.4
2	Perpendicular	Low	36.0	62.5
3	Perpendicular	Low	45.0	73.5
4	Parallel	Medium	46.2	72.3
5	Perpendicular	Medium	47.1	76.8
6	Perpendicular	Medium	21.5	48.3
7	Parallel	High	39.0	59.3
8	Parallel	High	46.8	73.4
9	Perpendicular	High	47.8	56.0

TABLE 18. BEARING STRENGTH PROPERTIES (e/D=2.0)

SUPRAL 150-T6

Specimen No.	Condition (to Strain)	EQS Range	Bearing Yield Strength Fbry, Ksi	Bearing Ultimate Strength Fbru, Ksi
1	Parallel	Low	63.1	76.4
2	Perpendicular	Low	45.2	79.8
3	Perpendicular	Low	45.9	84.8
4	Parallel	Medium	52.0	92.2
5	Parallel	Medium	54.3	81.7
6	Perpendicular	Medium	49.2	67.1
7	Parallel	High	54.1	66.8
8	Perpendicular	High	51.5	55.5
9	Perpendicular	High	52.8	63.2

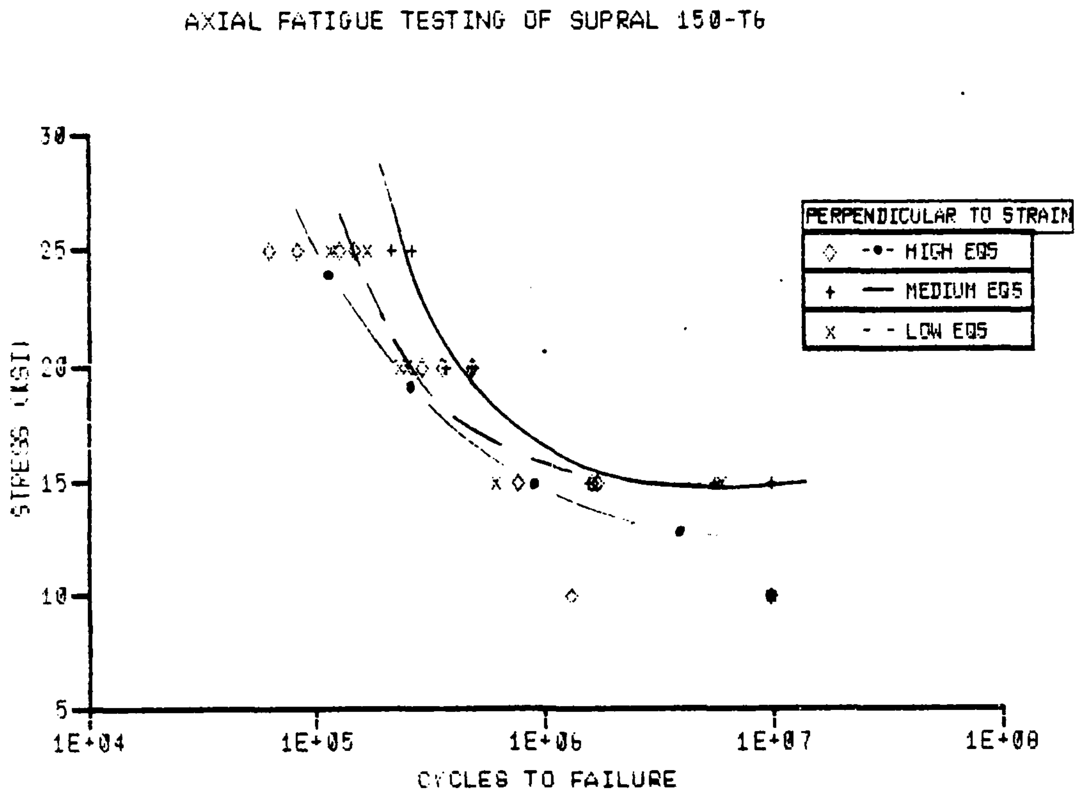


Figure 10. Axial Fatigue Properties of Smooth Specimens, Perpendicular to Strain - Supral 150-T6

Supral 150. This is due to the cladding which lowers the fatigue properties and masks the effect of equivalent strain on the fatigue life.

2.3.2.8 Fatigue Tests - Parallel to Strain (FRC Funded)

Tests were conducted on smooth ($K_T = 1$) fatigue specimens. The data is presented in the S-N curves in Figure 11. The curves are identical to the perpendicular to strain curves.

2.3.2.9 Electroconductivity

Electroconductivity measurements were made on heat treated (T6) Supral 150 discs and lips. As can be seen in Table 19, the percent IACS varies slightly as the equivalent strain is increased. Measurements were also recorded on non-heat treated material or as superplastically formed . Here the electroconductivity decreases as the equivalent strain is increased.

2.3.2.10 Metallography

Superplastically formed discs were bisected and five metallographic specimens were cut out along the diameter. The grains of the cladding were quite large (Figure 12) which is the probable cause of the lower fatigue life in the cladded Supral 150 and 220. The cladding was then ground off and the material was examined. The respective equivalent strains were recorded and average grain diameters were calculated (Table 20). The grains are similar to Supral 100 which shows that the cladding has no effect on the grain size of the superplastically formable alloy. Photomicrographs of Keller's reagent etched fine grain samples are shown in Figures 13 and 14.

2.3.3 Properties of Supral 220 Clad - T6

2.3.3.1 Smooth ($K_T = 1$) Tensile Tests

Tensile tests were conducted with specimens from perpendicular and parallel to the strain. The results are listed in Table 21. As noted in the table, many of the test specimens in the high equivalent strain range failed prior to yield and with minimal elongation. The relationship between tensile properties and percent EQS is demonstrated in Figure 15. Once again it can be noted that the properties decrease in the high EQS range.

2.3.3.2 Notched ($K_T = 3$) Tension Tests

Perpendicular and parallel to strain tensile specimens were tested. The results, shown in Table 22 and Figure 16 indicate a decrease in notched tensile strength in the high equivalent strain range.

2.3.3.3 Compression Tests

Perpendicular and parallel strained test specimens were tested in compression and the results are shown in Table 23 and Figure 17. Compression yield and modulus test results tend to scatter even when specimens are taken from

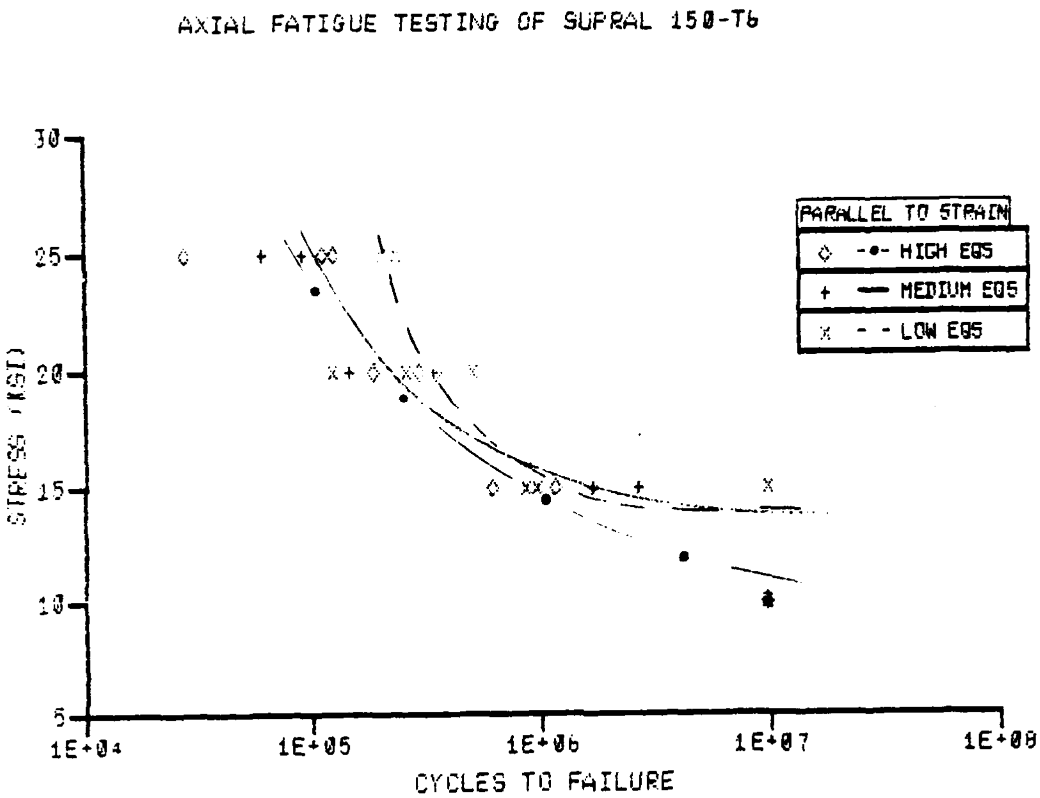


Figure 11. Axial Fatigue Properties of Smooth Specimens, Parallel to Strain - Supral 150-T6

TABLE 19. ELECTROCONDUCTIVITY MEASUREMENTS OF SUPRAL 150 HEAT TREATED (T6) VERSUS AS SUPERPLASTICALLY FORMED

(% IACS)

EQS	Heat Treated	As Superplastically Formed
0% (Flange	48.5-50.0	54.5-56.0
Low Range 25-75%	38.5-44.5	51.0-52.0
Medium Range 75-150%	40.5-43.0	44.0-52.0
High Range 150-250%	37.5-42.0	42.0-47.5

Heat Treatments

Supral 100 and Supral 150	-	530°C for 30 minutes, quench into 30-35% quendilia (glycol), age for 10.5 hours at 177°C, air cool.
Supral 220	-	523°C for 60 minutes, quench into 30-35% quendilia (glycol), age for 8 hours at 190°C, air cool.

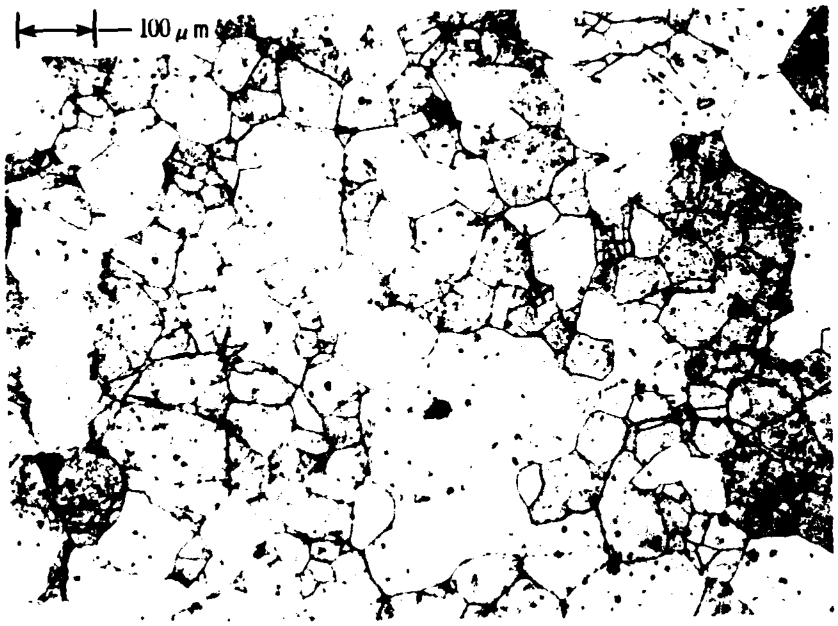
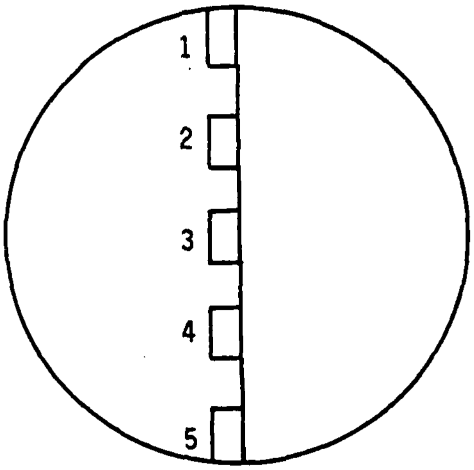


Figure 12. Supral 150 Cladding (100X)

TABLE 20. GRAIN SIZE MEASUREMENTS - SUPRAL 150



Position Number	% Equivalent Strain	Average Grain Diameter Microns
Disk 1 (SP2330-105/35)		
1	52.6	3.8-4.5
2	58.8	4.0-4.3
3	67.2	4.4-4.7
4	58.6	4.0-4.5
5	53.8	4.0-4.3
Disk 2 (SP2330-127/35)		
1	102.6	5.6-6.2
2	139.4	5.0-5.6
3	163.3	6.0-6.6
4	154.8	5.6-6.2
5	113.5	5.6-6.2
Disk 3 (SP2330-120/35)		
1	157.9	4.2-4.8
2	232.2	4.2-4.8
3	248.8	5.6-6.4
4	204.3	4.2-4.8
5	155.2	4.2-4.8

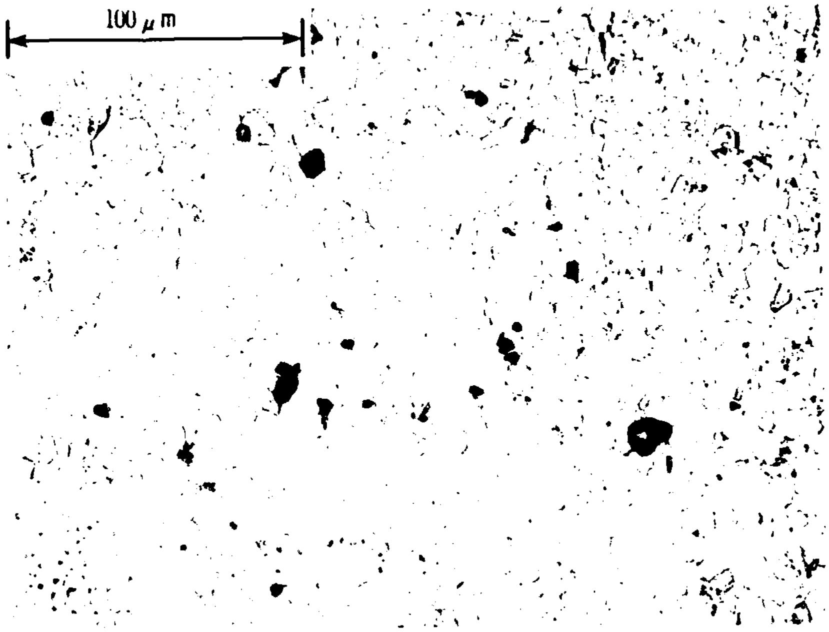


Figure 13. Photomicrograph of Etched Supral 150 - Disk SP2330-105/35-Position 5 (400X)

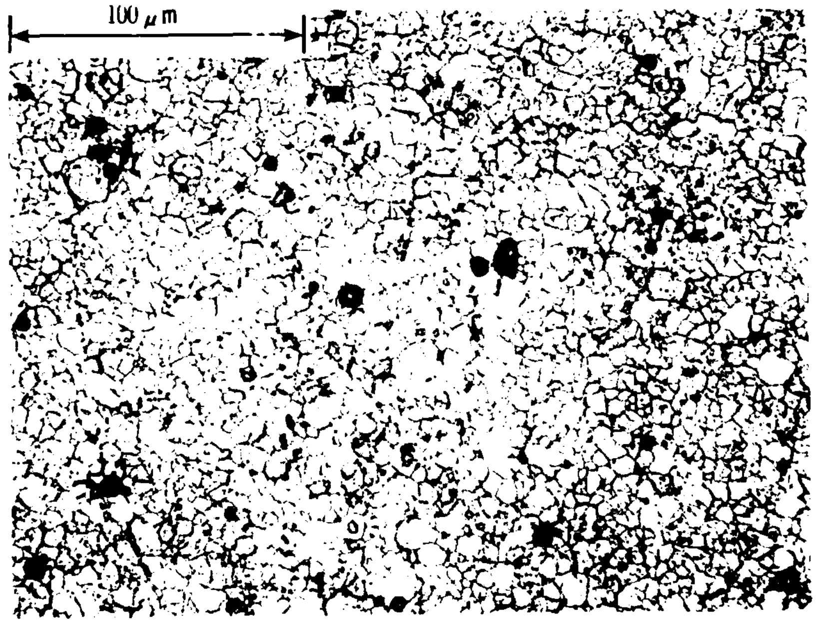


Figure 14. Photomicrograph of Etched Supral 150 - Disk SP2330-120/35-Position 1 (400X)

<u>Note</u>: The dark spots are due to CuAl2 precipitants.

TABLE 21. AVERAGE TENSILE PROPERTIES AT K_T=1

SUPRAL 220 - T6 CLAD

Condition	EQS Range	Fty, Ksi		Ftu, Ksi		Elongation % in 2"		E Modulus 10^6 psi	
		$\bar{X}$	σ_{n-1}	$\bar{X}$	σ_{n-1}	$\bar{X}$	σ_{n-1}	$\bar{X}$	σ_{n-1}
Parallel to Strain	Low	50.9	0.86	60.1	1.28	8.1	0.73	10.2	0.59
	Medium	50.1	1.29	58.6	1.23	7.1	0.56	9.8	0.82
	High	48.1*	0.97	42.7**	3.22	1.4**	0.25	10.1	0.89
	High	-		51.7***	1.74	2.3***	0.76	-	
Perpendicular to Strain	Low	52.6	0.42	61.3	0.95	7.4	0.83	10.4	0.79
	Medium	50.7	0.78	59.7	0.77	7.5	0.59	9.9	0.69
	High	47.5*	2.29	41.6**	2.90	1.8**	0.27	10.8	0.94
	High	-		50.3***	3.14	3.0***	1.06	-	
Perpendicular and Parallel to Strain	Low	51.7	1.08	60.7	1.27	7.8	0.84	10.3	0.68
	Medium	50.4	1.07	59.2	1.18	7.3	0.60	9.8	0.74
	High	47.8*	1.59	42.2**	2.91	1.6**	0.32	10.4	0.95
	High	-		51.1***	2.40	2.6***	0.93	-	

* Some of the test specimens failed prior to 0.2% offset yield. These values are listed separately.

** Value for specimens which failed prior to 0.2% offset yield. Parallel - 4 specimens, perpendicular - 7 specimens

*** Value for specimens which failed after the 0.2% offset yield. Parallel - 7 specimens, perpendicular - 5 specimens

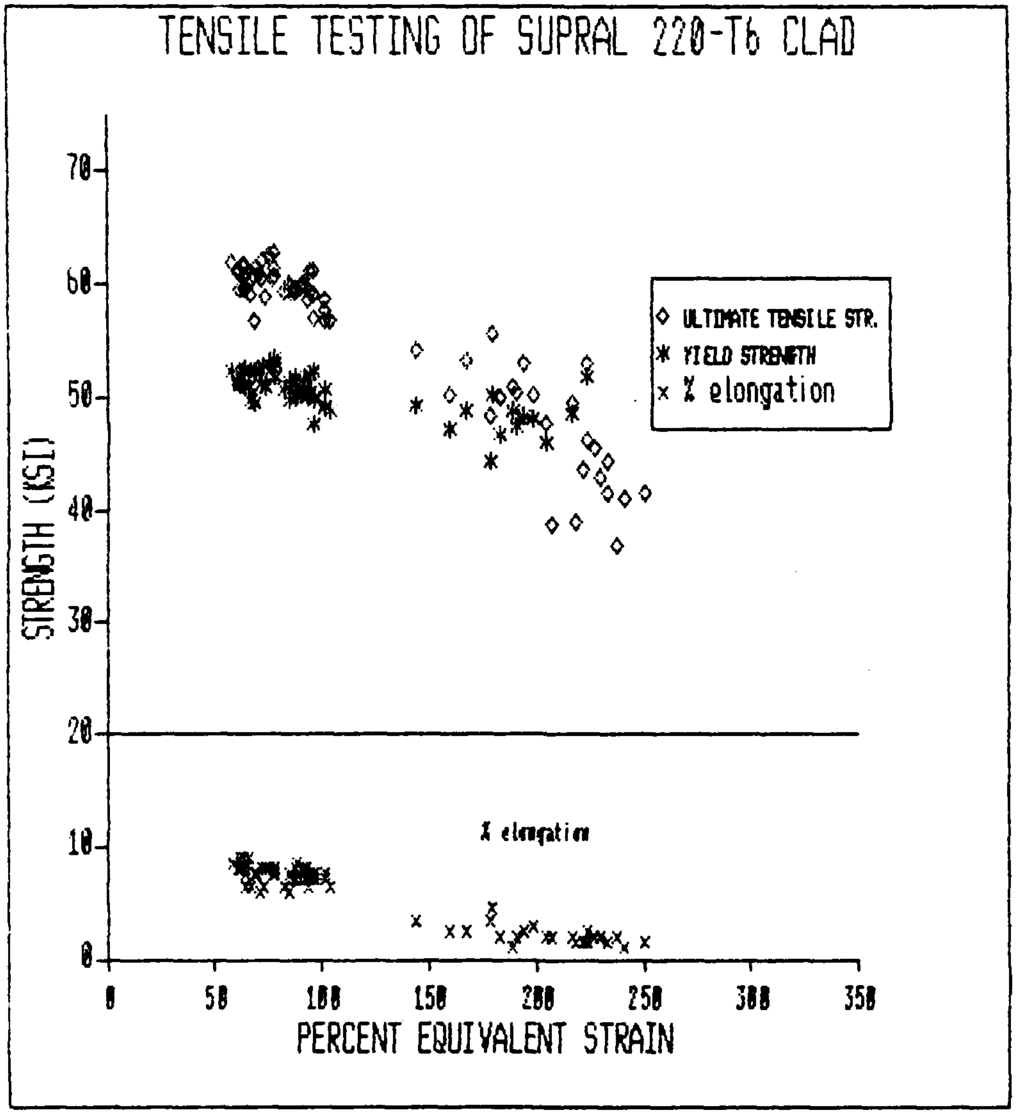


Figure 15. Tensile Properties of Supral 220 Clad versus EQS
(Each point denotes a test result)

TABLE 22 . AVERAGE NOTCHED TENSILE PROPERTIES AT K_T=3

SUPRAL 220 - T6 CLAD

Condition	EQS Range	NTS, Ksi		NTS/Fty	NTS/Ftu
		$\bar{X}$	σ_{n-1}		
Parallel to Strain	Low	50.1	2.30	0.984	0.833
	Medium	48.3	3.59	0.964	0.824
	High	42.0	5.76	0.873	0.812
Perpendicular to Strain	Low	50.1	2.71	0.952	0.879
	Medium	51.5	2.13	1.016	0.863
	High	43.6	5.46	0.918	0.867
Perpendicular and Parallel to Strain	Low	50.1	2.45	0.967	0.825
	Medium	49.9	3.32	0.990	0.843
	High	42.9	5.48	0.895	0.839

TABLE 23. AVERAGE COMPRESSIVE STRENGTH PROPERTIES

SUPRAL 220 - T6 CLAD

Condition	EQS Range	Fcy, Ksi		E Modulus 10^6 psi	
		$\bar{X}$	σ_{n-1}	$\bar{X}$	σ_{n-1}
Parallel to Strain	Low	53.4	7.55	8.8	0.84
	Medium	67.6	1.40	10.1	0.99
	High	61.2	4.26	11.5	1.12
Perpendicular to Strain	Low	63.2	2.56	10.5	0.41
	Medium	50.4	8.86	8.7	0.99
	High	62.1	4.89	10.7	0.69
Perpendicular and Parallel to Strain	Low	57.9	7.58	9.6	1.11
	Medium	59.0	10.85	9.4	1.17
	High	61.7	4.40	11.1	0.98

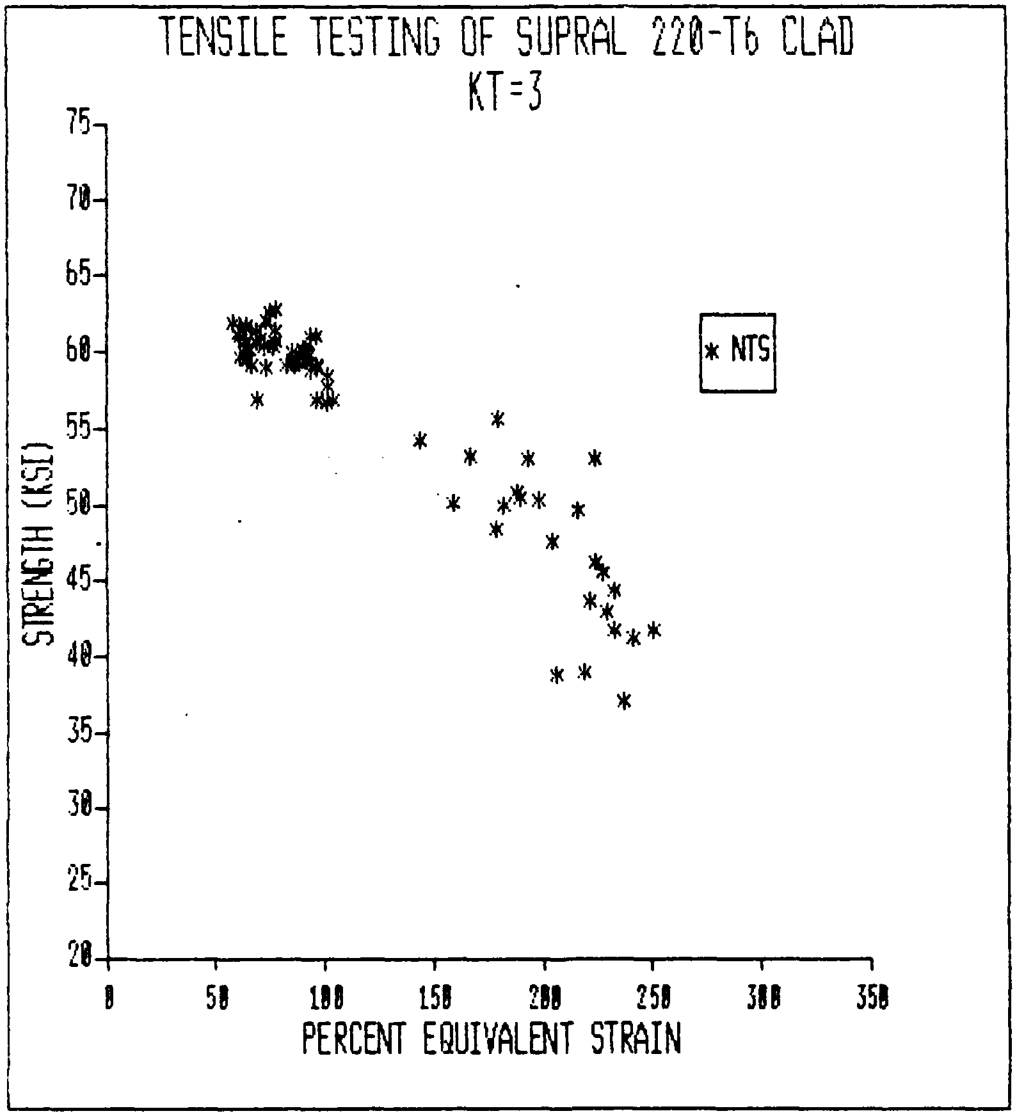


Figure 16. Notched Tensile Strength of Supral 220 Clad versus EQS (Each point denotes a test result)

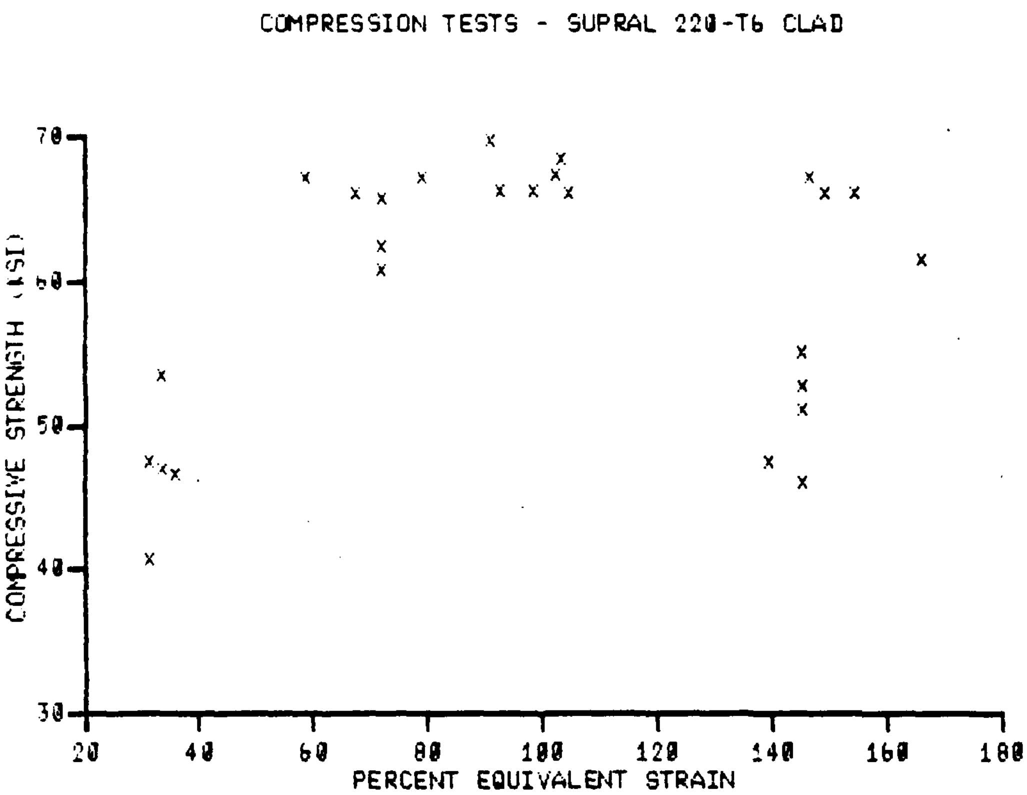


Figure 17. Compressive Strength of Supral 220 Clad versus EQS
(Each point denotes a test result)

adjacent sites. Unlike other property tests, increasing equivalent strain did not reduce the compressive properties measured. It is postulated that the variations in test specimen and clad thickness, due to superplastic stretching, may be responsible for these results. It is planned to further investigate this effect with a larger test sample set.

2.3.3.4 Bearing Tests - e/D = 1.5

Tests were conducted on bearing specimens from both perpendicular and parallel to the strain direction. The test results are given in Figure 18 and Table 24. The ultimate bearing strength increases slightly from 40 to 65% EQS and then decreases after 150% EQS.

2.3.3.5 Bearing Tests e/D - 2.0

Bearing tests were run on specimens taken from the perpendicular and parallel to superplastic straining condition. The test results shown in Figure 19 and Table 24 show scatter in the lower EQS range. It is postulated that non-uniform thickness distribution due to superplastic stretching may be responsible. Further investigation of this anomaly is planned.

2.3.3.6 Fatigue Test - $K_T = 1$

Axial fatigue tests were performed on smooth specimens parallel to strain. The S-N curve is shown in Figure 20.

The high EQS range specimens failed after fewer cycles than the medium and low EQS range specimens. This is caused by the increase in cavitation in the high EQS range. The cavities are initiation sites for fatigue cracks.

2.3.3.7 Fatigue Tests - $K_T = 3$

Axial fatigue tests were performed on notched specimens perpendicular to strain. The S-N curve is shown in Figure 21. The three curves (low, medium and high EQS ranges) are nearly identical. The notch specimens are not affected by equivalent strain.

2.3.3.8 Stress Corrosion

Direct tension stress corrosion specimens were tested in alternate immersion 3.5 percent sodium chloride solution in accordance with ASTM G44. Low-, medium-and high-range EQS specimens were tested at 48.75 Ksi for 30 days without failure. At the stress level, which is 95% of the yield strength, the material showed extremely good corrosion properties.

2.3.3.9 Hardness Values

Rockwell B hardness measurements were made on discs and lips of varying equivalent strain levels (Table 25). The low and medium EQS level specimens had similar readings while the high EQS range was 9-10 R_B readings lower.

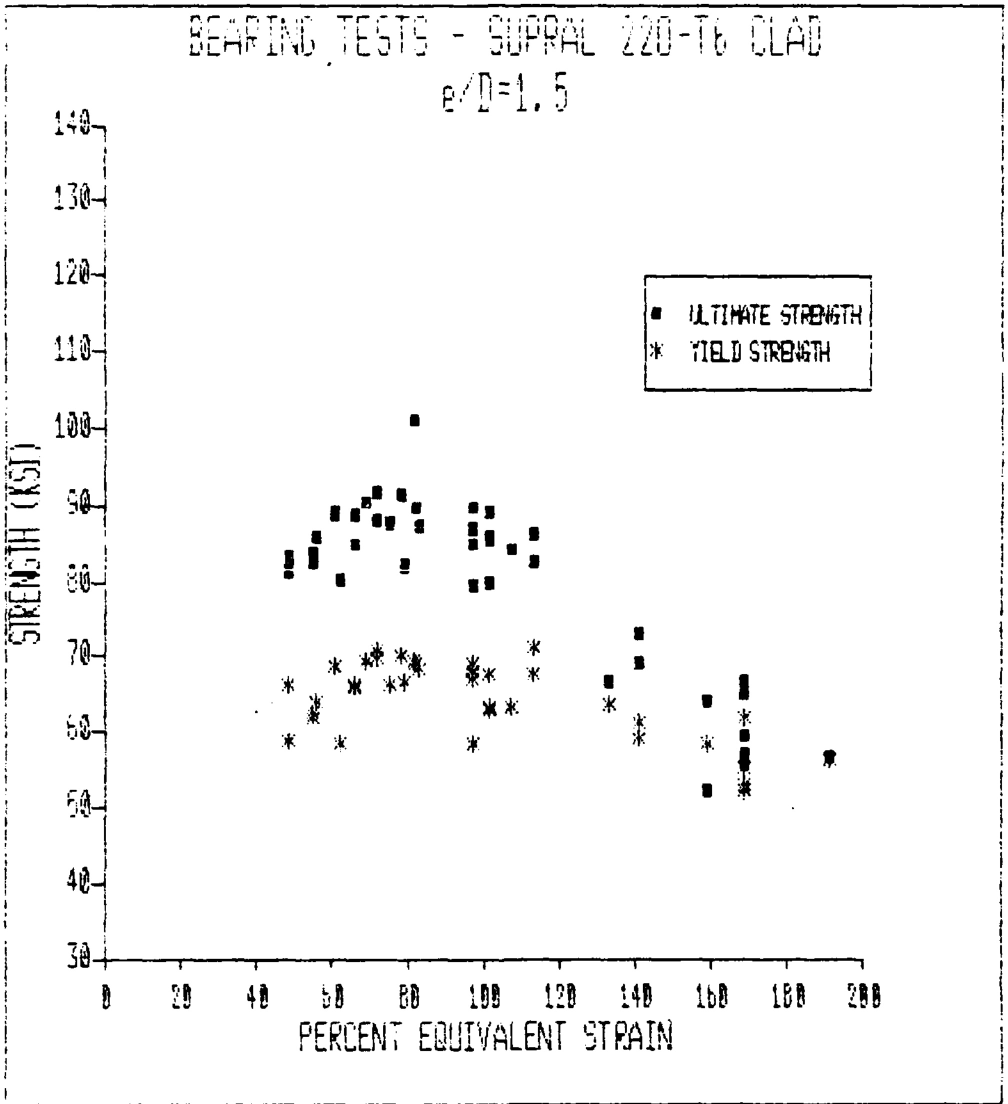


Figure 18. Bearing Strength Properties (e/D=1.5) of Supral 220 Clad versus EQS

(Each Point Denotes a Test Result)

TABLE 24. AVERAGE BEARING STRENGTH PROPERTIES

SUPRAL 220 - T6 CLAD

Property	EQS Range	Bearing Yield Strength, Fbry, Ksi				Bearing Ultimate Strength Fbru, Ksi			
		e/D=1.5		e/D=2.0		e/D=1.5		e/D=2.0	
		$\bar{X}$	σ_{n-1}	$\bar{X}$	σ_{n-1}	$\bar{X}$	σ_{n-1}	$\bar{X}$	σ_{n-1}
Parallel to Strain	Low	62.5	4.1	71.2	5.6	83.2	2.9	101.9	9.5
	Medium-Low*	68.7	1.5	80.2	2.1	92.2	5.2	114.6	6.1
	Medium	66.2	2.8	77.2	2.6	85.0	3.6	90.3	3.5
	High	60.9	3.9	60.6**	8.1	69.2	4.2	63.7	1.1**
	High							56.4	1.6***
Perpendicular to Strain	Low	66.0	2.0	68.9	4.5	85.3	2.9	93.0	11.9
	Medium-Low*	68.7	2.2	77.9	3.7	88.9	1.1	112.0	3.6
	Medium	65.0	4.7	75.1	6.2	85.1	3.0	93.1	4.2
	High	56.7	4.4	58.3**	0.1	61.8	5.4	65.5	6.9**
	High							57.3	8.1***
Perpendicular and Parallel to Strain	Low	63.9	3.7	70.1	4.9	84.0	2.9	97.5	11.2
	Medium-Low*	68.7	1.6	79.2	3.0	91.0	4.3	113.4	5.2
	Medium	65.6	3.7	76.2	4.[illegible]	[illegible]5.1	3.2	91.7	4.0
	High	58.6	4.5	59.8**	6.4	64.5	6.4	64.3	6.4**
	High							57.0	6.3***

* Medium-Low = 60-85% EQS

** Some of the test specimens failed prior to yield. These values are excluded. Parallel - 2 specimens, Perpendicular - 4 specimens.

*** Value for specimens which failed after yield.

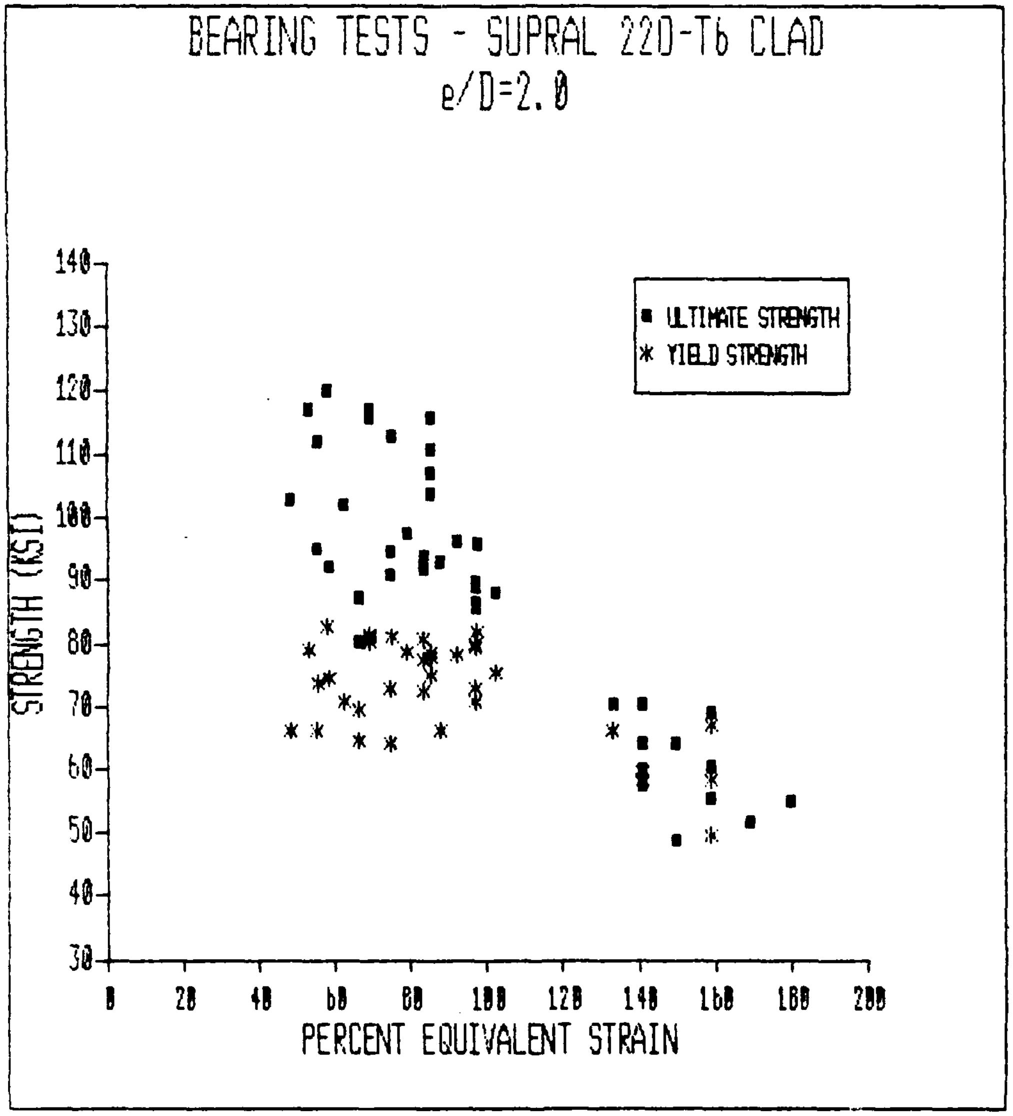


Figure 19. Bearing Strength Properties (e/D=2.0) of Supral 220 Clad versus EQS
(Each point denotes a test result)

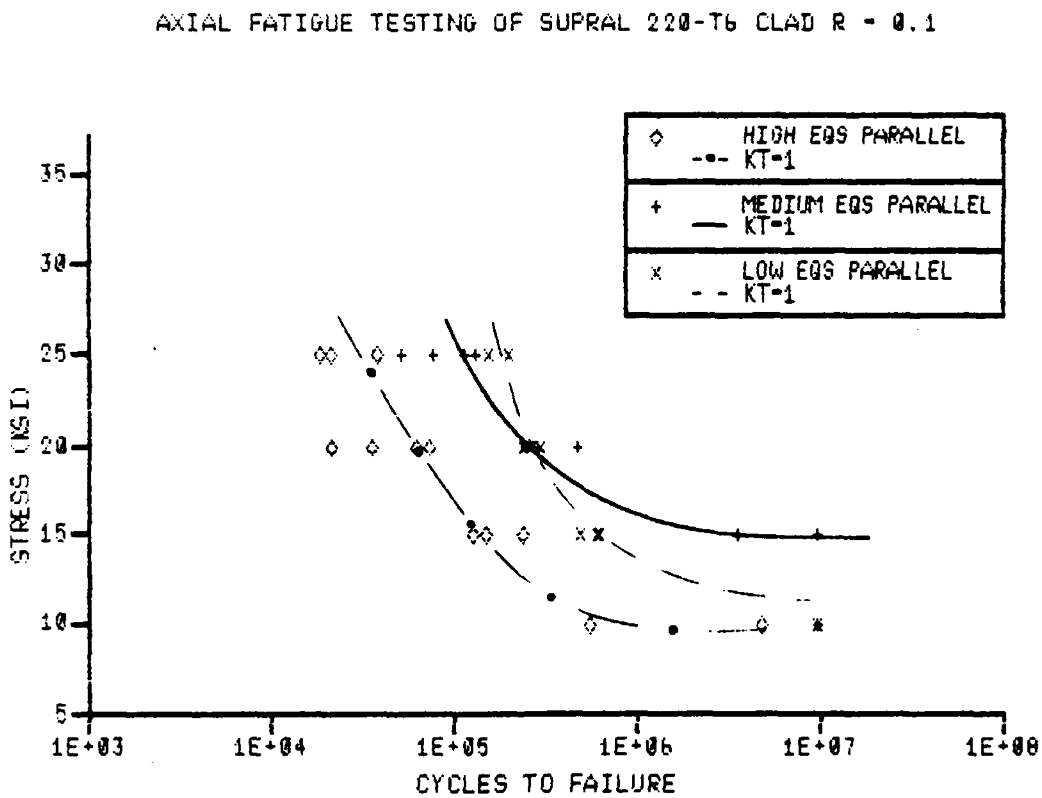


Figure 20. Axial Fatigue Properties of Smooth Specimens, Parallel to Strain, (K_T=1, R=0.1)
(Each point denotes a test result)

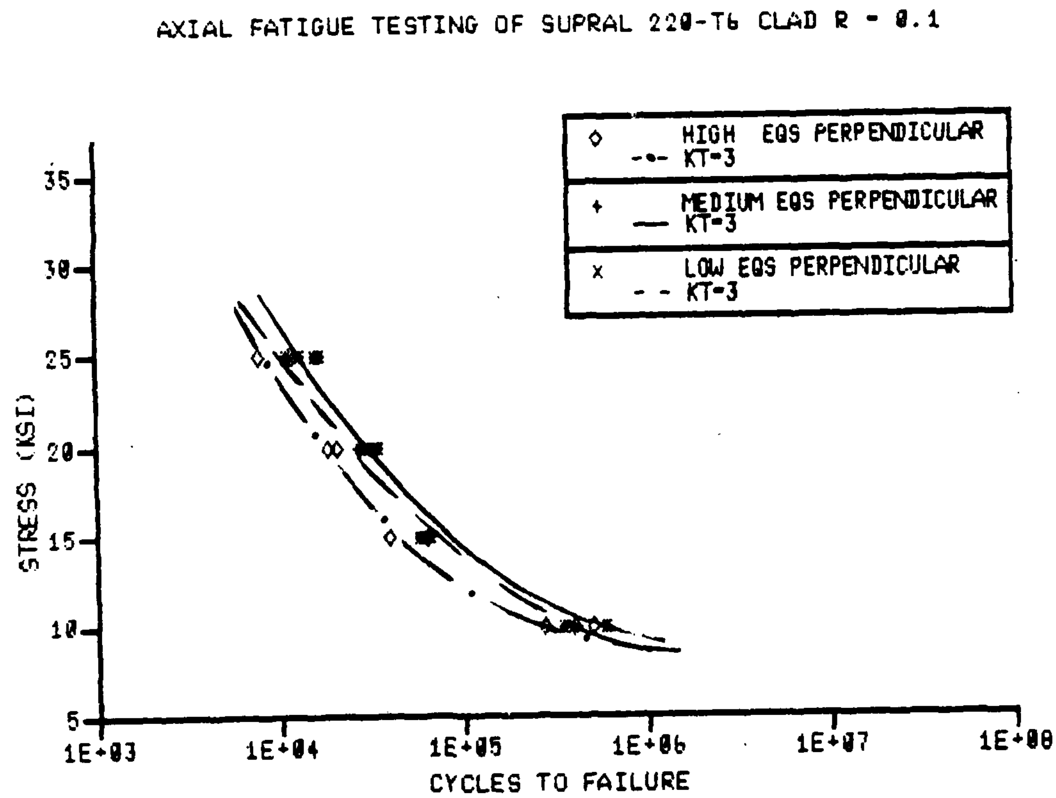


Figure 21. Axial Fatigue Properties of Notched Specimens, Perpendicular to Strain (K_T=3, R=0.1)

(Each point denotes a test result)

TABLE 25. HARDNESS READINGS - SUPRAL 220

ROCKWELL B

Equivalent Strain	Number of Readings	Hardness Value
Low	26	64.7 $\sigma_{n-1} = 2.6$
Medium	26	63.0 $\sigma_{n-1} = 3.4$
High	26	53.6 $\sigma_{n-1} = 1.9$

TABLE 26. GRAIN SIZE MEASUREMENTS - SUPRAL 220-T6

EQS Range	Average Grain Size (Microns)
Low	4.5 - 6.0
Medium	4.5 - 6.0
High	3.0 - 5.5

2.3.3.10 Cavitation

Cavitation or microvoid formation and growth is a phenomenon related to metallographic structure and amount and rate of strain. See Section VI, Reference 3, for detailed discussion. Cavitation affects the mechanical properties of the Supral dependent on the amount of strain as can be seen herein. To study this effect, discs, with controlled total strain, were sectioned and unetched metallographic specimens prepared. Cavitation was measured by calculating the surface area of the void using the linear intercept method at 100X. While automated measuring devices exist, Fairchild found that operator measurement gave comparable results. Measurement by Archimedian density proved operator and technique sensitive and yielded disparities in results. The maximum percentage of cavitation observed was in the high strained areas. When observed microscopically 6-7 percent cavitation was observed in general areas with greater than 180 percent EQS. In most cases, cavitation was approximately 1-2 percent of the total area (at 100X). The one difficulty in examining cavitation in the high EQS levels is the size of the specimen. The specimens are extremely thin, under 0.025 inch, and therefore difficult to metallographically prepare and to analyze. Figure 22 shows examples of microcavitation. Many of the cavities appear at the triple grain boundary point.

2.3.3.11 Metallography

Specimens were prepared with varied equivalent strains. The grain size was measured using the linear intercept method at 400X magnification. Table 26 shows the range for average grain size in each EQS group. Figures 23 and 24 show examples of the microstructure of the Supral 220 alloy. For surface views, the cladding was ground off. Cavitation is enhanced by the etchant and therefore in comparing the etched and unetched sample, the etched sample appears to have more cavitation. Similar to the other Supral alloys, the Supral 220 grains were fine.

2.3.3.12 Corrosion Salt Spray

Samples of Supral 220 were tested per ASTM B117 in a salt fog chamber for 168 hours. Supral 220 was more resistant to pitting than the Supral 100 and 150. All of the specimens retained their gloss and color which is evidence of little attack by the salt solution.

2.3.4 Tests Conducted by AFWAL/FIBE

2.3.4.1 Crack Propagation Tests

Crack propagation tests were conducted on Supral 220-T6 clad. The Walker equation was utilized to compare Supral 220, 7075 and 6061. The constant values used for 7075 were $C=3.26 \times 10^{-9}$, $n=0.5$ and $n=3.39$ and for 6061 were $C=7.56 \times 10^{-9}$, $n=0.6$ and $n=2.82$. The results are given in Figures 25-28. The crack growth rates for Supral 220 were not as good as those for 2024-T3 and 6061-T6, but noticeably better than those for 7075-T6.

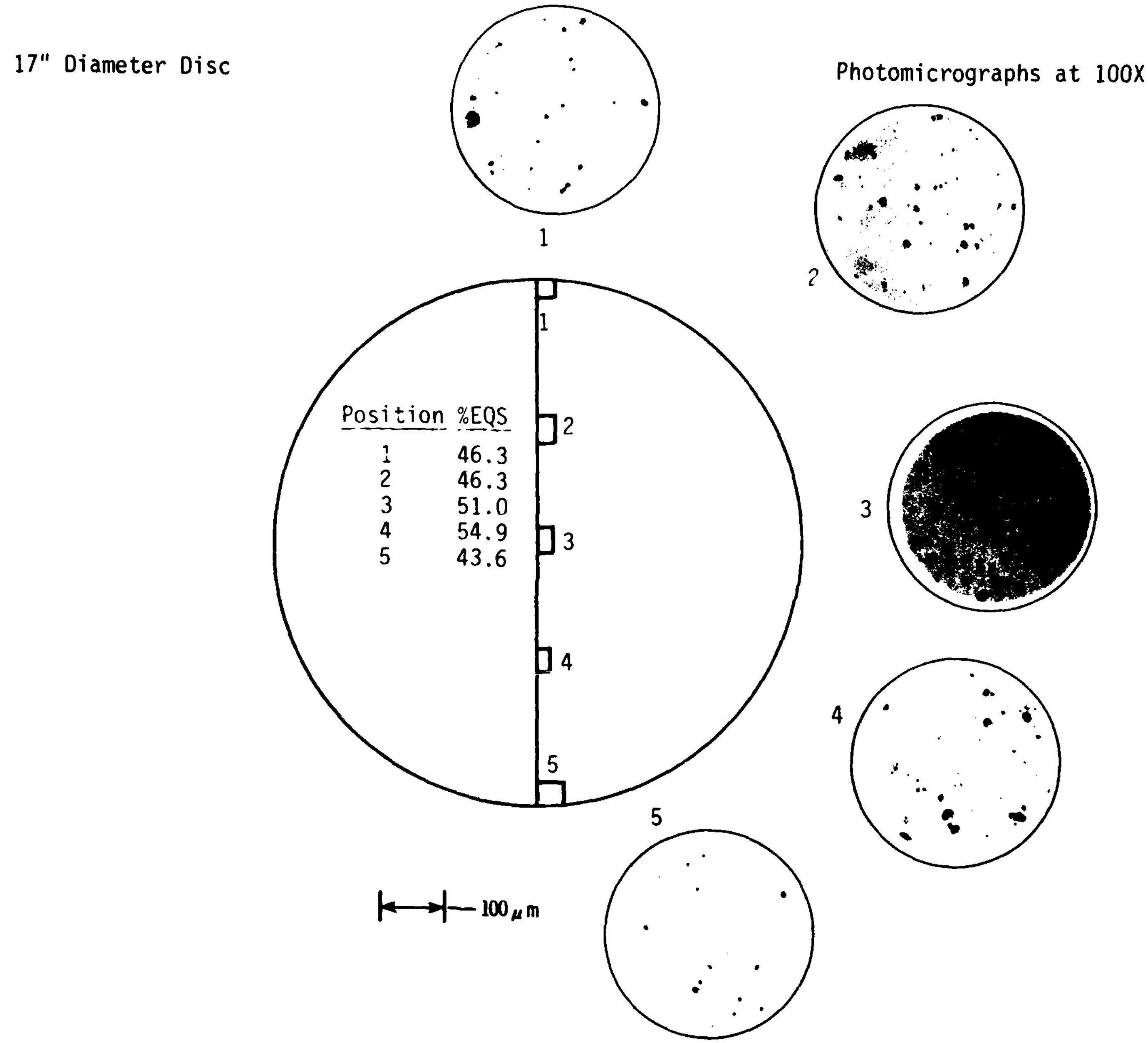


Figure 22. Microcavitation Examination - Supral 220

MICROSTRUCTURE OF SUPRAL 220 CLAD
(SPECIMEN C38/39-28 -84% EQS)

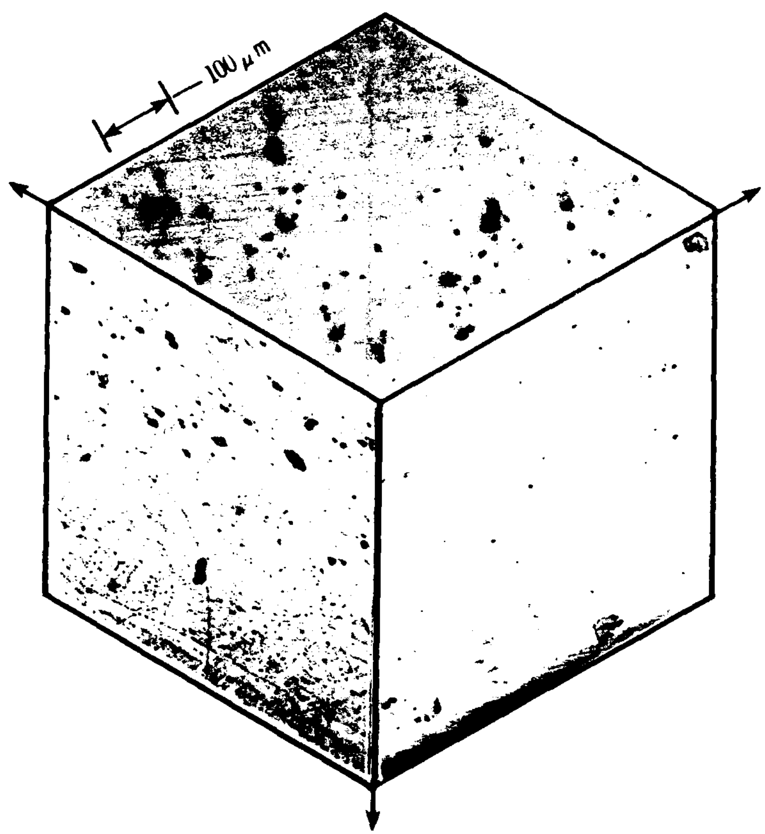


Figure 23. Unetched, 100X

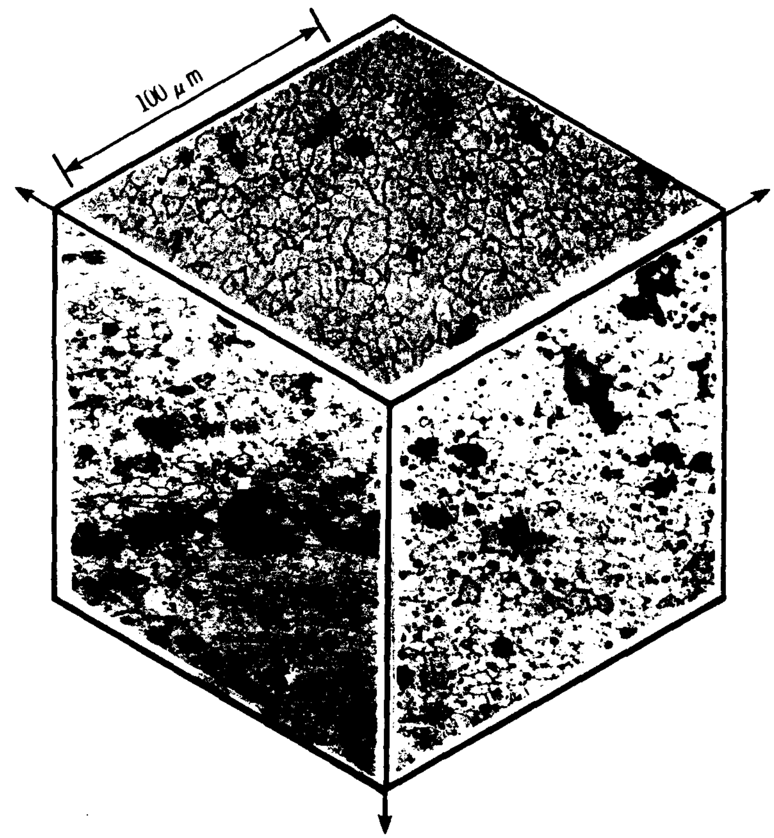


Figure 24. - Etched 400X

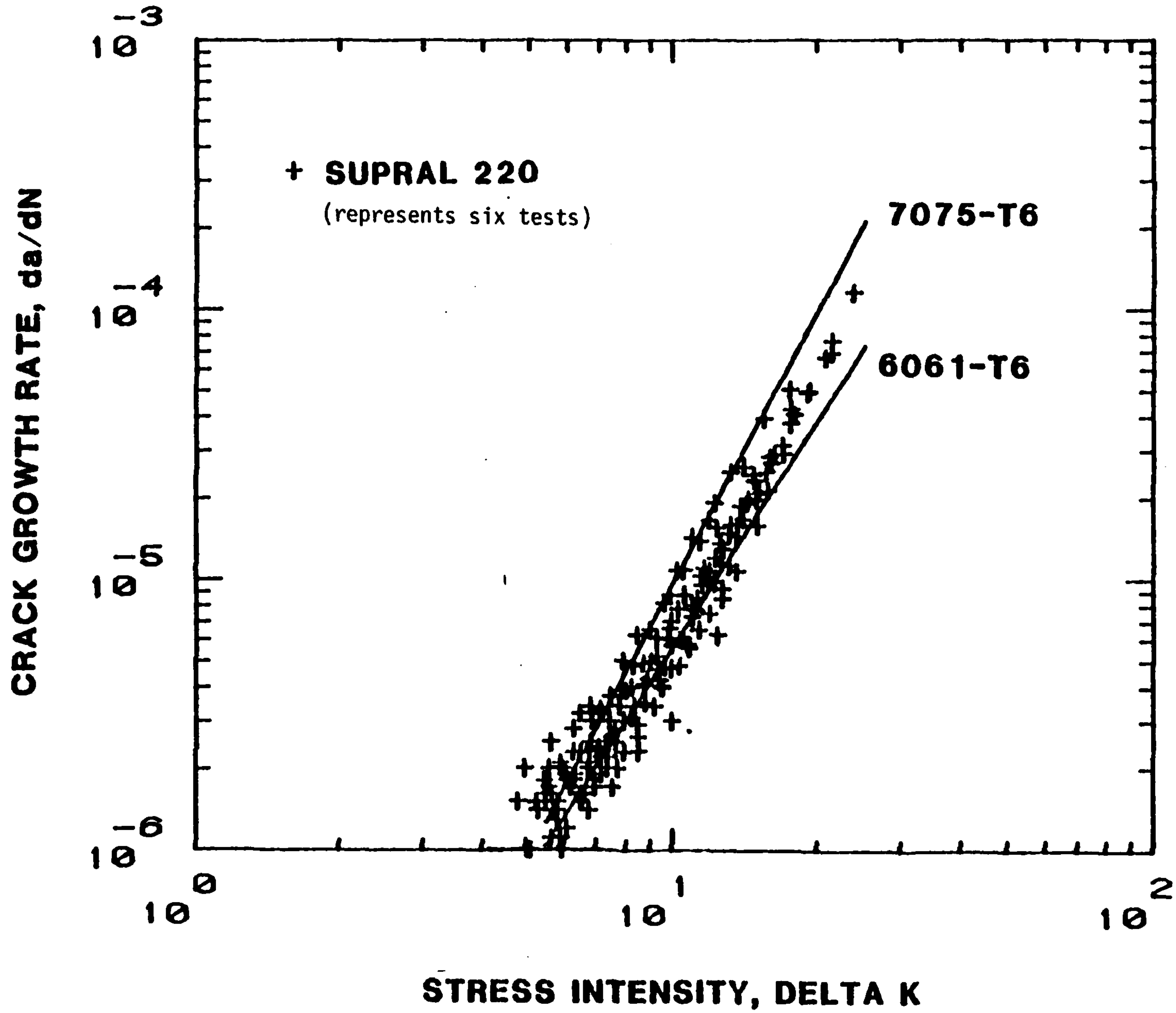


Figure 25. Crack Growth Rates for Supral 220 versus 7075-T6 and 6061-T6 at 10 Ksi, R=0.1

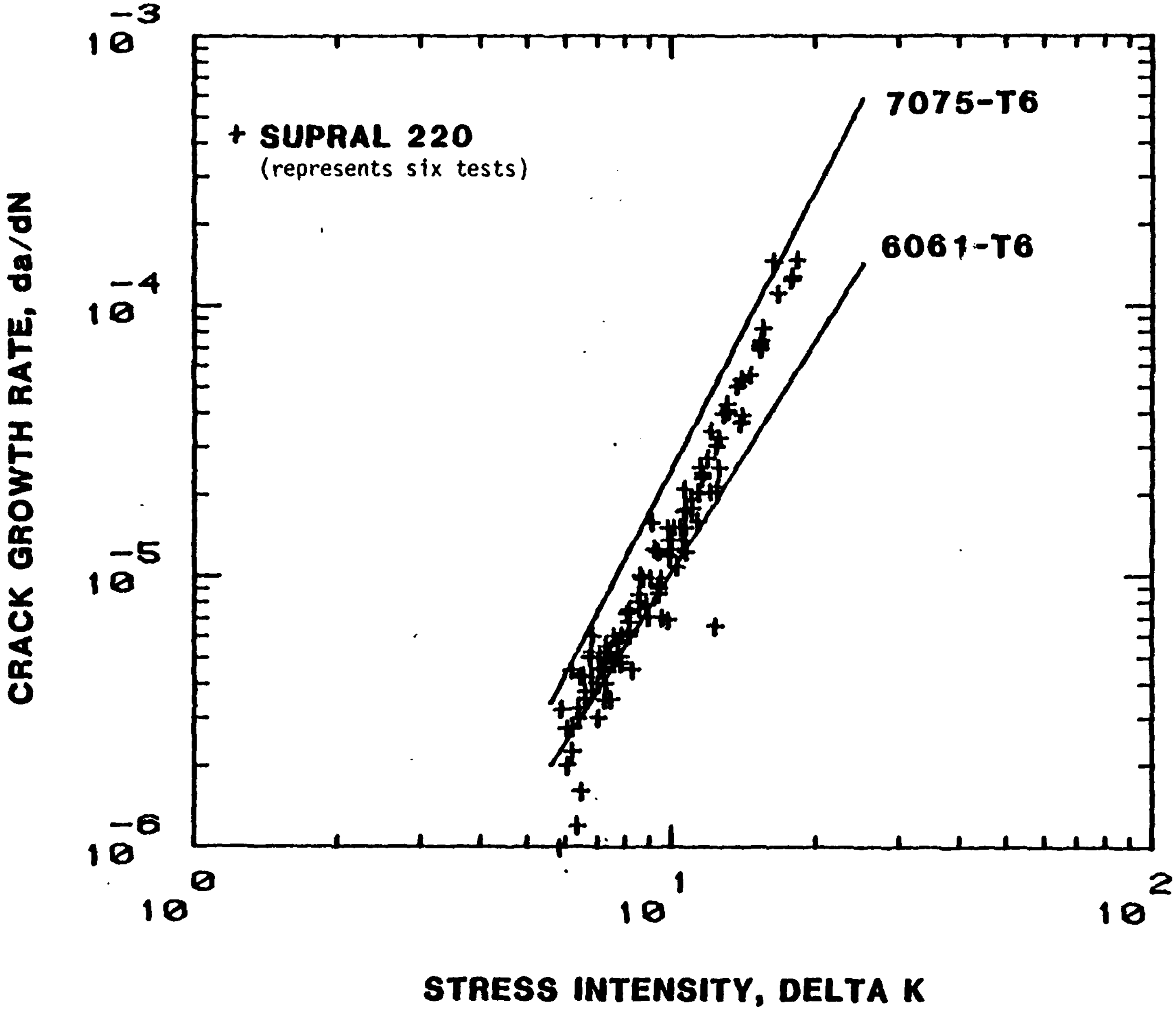


Figure 26. Crack Growth Rates for Supral 220 versus 7075-T6 and 6061-T6 at 20 Ksi, R=0.5

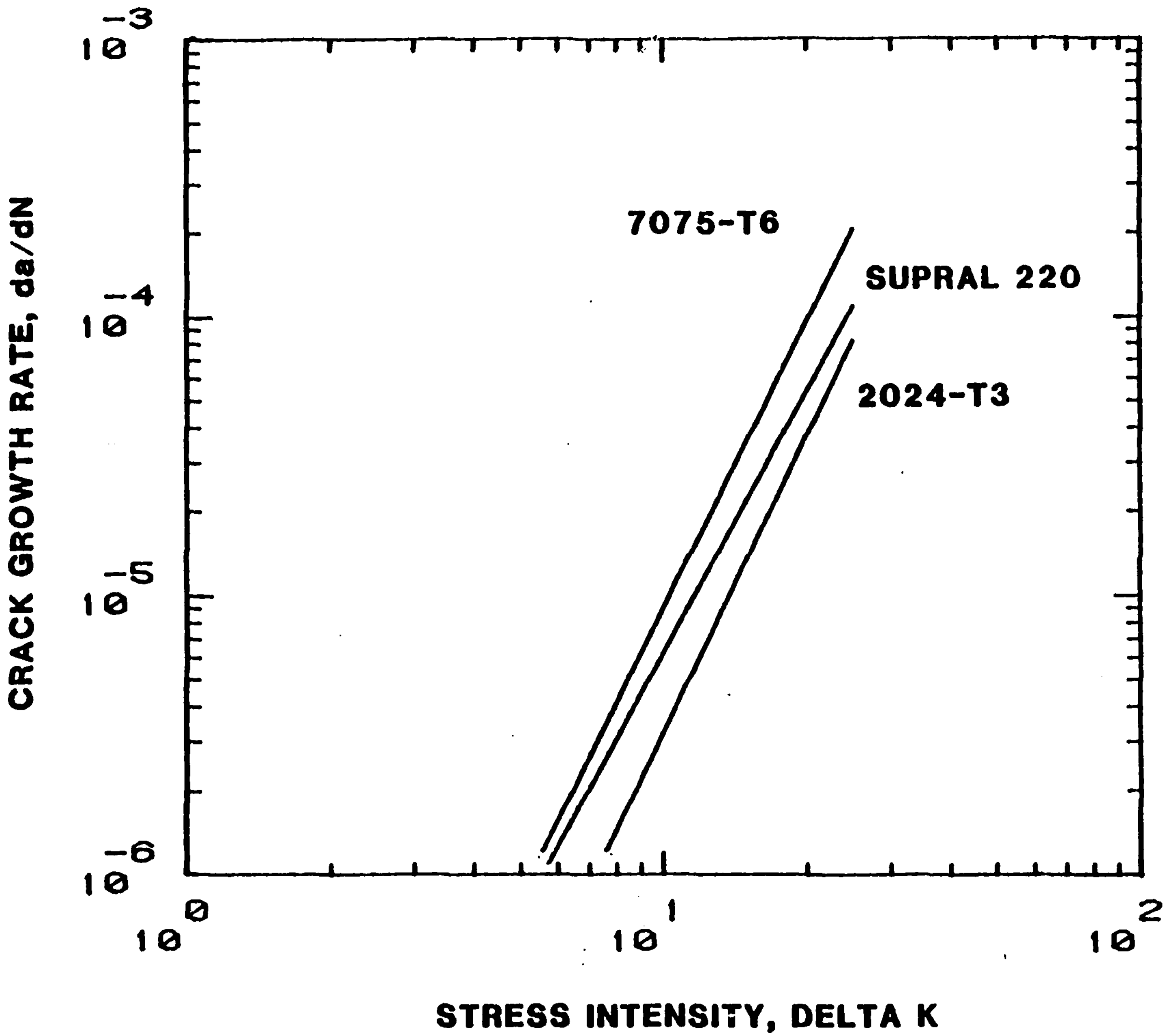


Figure 27. Crack Growth Rates for Supral 220 versus 7075-T6 and 2024-T3 at 10 Ksi, R=0.1

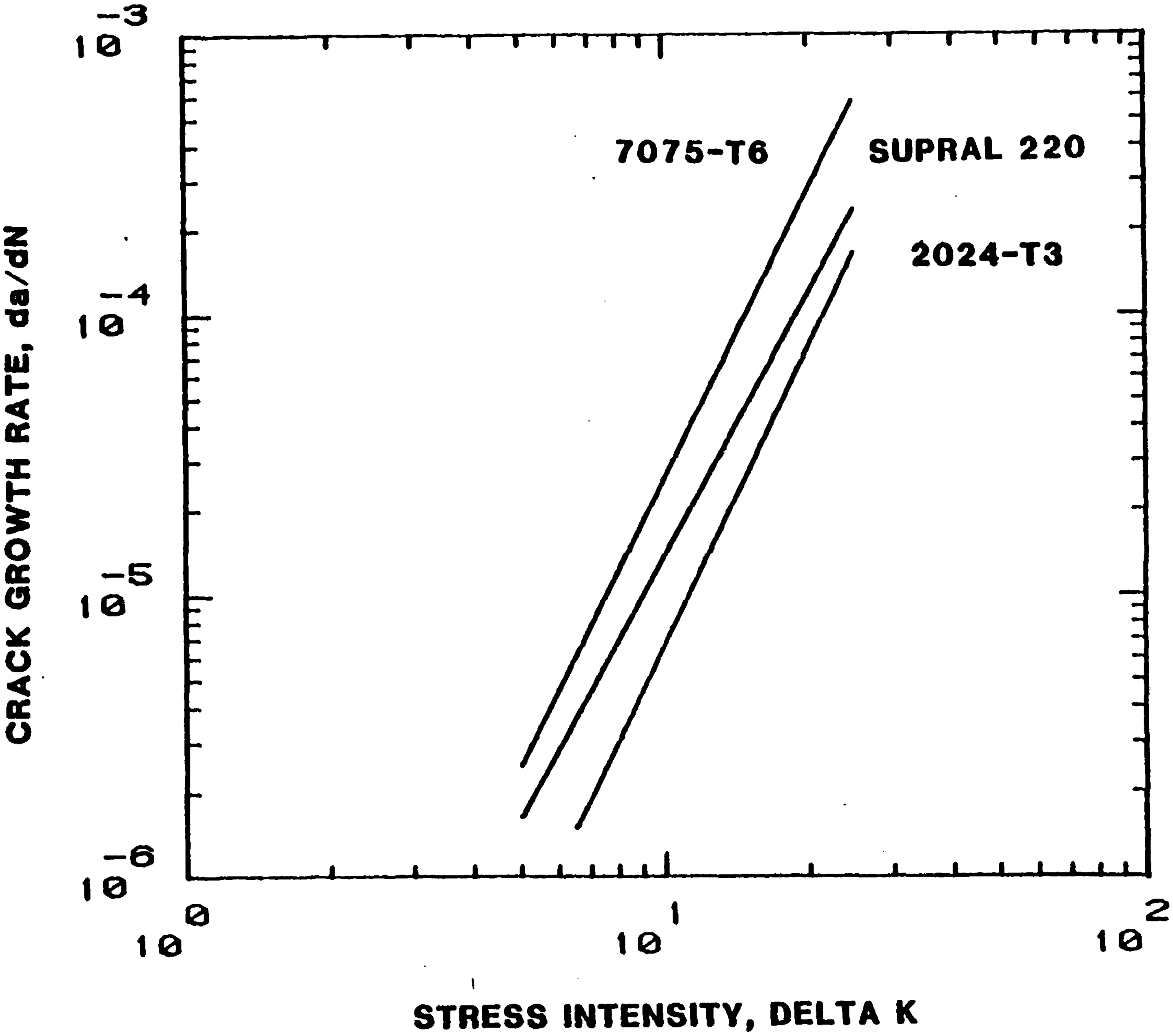


Figure 28. Crack Growth Rates for Supral 220 versus 7075-T6 and 2024-T3 at 20 Ksi, R=0.5

Delta (Δ K) was calculated using the following equations:

$$\Delta K = \Delta\sigma\sqrt{\pi a}\,\beta$$

$$\beta = 1 + 0.256\left(\frac{a}{w}\right) - 1.152\left(\frac{a}{w}\right)^2 + 12.19\left(\frac{a}{w}\right)^3$$

Growth rates were calculated by the secant method - $\Delta a/\Delta N$

2.3.4.2 Fatigue Tests

Tests were conducted on K_T=1, R=0.1 fatigue specimens. The parallel to strain specimens had longer fatigue lives than the perpendicular specimens (Table 27). Many of the failures occurred at surface defects caused by the die. In production, as Fairchild Republic has seen on the A-10 purge duct, the surface defects are eliminated. The fatigue testing (K_T=1, K_T=3) performed by Fairchild Republic did not show failure at surface defects.

2.3.4.3 Tensile Tests

Tests were conducted on perpendicular and parallel specimens. The results are given in Table 28.

2.3.4.4 Rain Erosion Tests

Rain erosion test specimens, prepared at Fairchild, were evaluated for rain erosion performance at Wright-Patterson Air Force Base. The six Supral 220 clad specimens were tested on a rotating arm apparatus at 500 mph in a 1-inch/hour simulated rainfall. The rotating arm facility consists of an 8-foot double-arm propeller blade mounted horizontally and powered by a 400-HP motor. A pipe ring with hypodermic needles is positioned to spray controlled droplets on the specimens which are inserted in the blade tips.* A stroboscopic unit and closed circuit TV camera enables observation of the specimen while running. Table 29 gives the results of the rain erosion test.

The Supral 220 clad performed much better than expected, especially for a non-chemically coated or treated aluminum specimen.

2.3.5 Manufacturing Processes

2.3.5.1 Chemical Cleaning

Supral alloys were chemically cleaned and deoxidized in the pilot line of Fairchild's research laboratory prior to application of chemical conversion coating (Alodine) in accordance with MIL-C-5541, Rev. E. The alodined specimens were exposed to salt fog exposure (MIL-C-81706) in an environmental test chamber for 168 hours for corrosion resistance evaluation.

Other specimens were sulphuric acid anodized in accordance with MIL-A-8625, Type II, Class 1 requirements and exposed for 336 hours in the salt fog environmental chamber.

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*Provided by Charles J. Hurley, Principal Investigator, University of Dayton Research Institute Coating Group, Dayton, Ohio

TABLE 27. RESULTS OF FATIGUE TESTS AT AFWAL
SUPRAL 220 - SOLUTION HEAT TREATED AND AGED (T6) CONDITION

Specimen No.	% EQS	Strain Direction	Maximum Stress (Ksi)	Cycles to Failure
1	64.0	Parallel	40	57,270
2	71.1	Parallel	40	59,000
3	87.4	Perpendicular	20	692,220
4	92.0	Perpendicular	20	435,550
5	71.1	Perpendicular	20	516,070
6	74.9	Perpendicular	20	580,700
7	78.9	Perpendicular	20	696,410
8	87.4	Perpendicular	20	547,430
9	96.8	Perpendicular	20	427,590
10	71.1	Parallel	20	1,583,840
11	71.1	Parallel	20	715,610
12	64.0	Parallel	20	1,120,630
13	71.1	Parallel	20	1,027,220
14	71.1	Parallel	20	1,973,800
15	67.4	Parallel	20	3,677,320

40 Ksi - 10 HZ

20 Ksi - 30 HZ

$K_T=1$, R=0.1

TABLE 28. TENSILE RESULTS ON SUPRAL 220-T6 CLAD
(Test Performed at AFWAL)

Specimen No.	% EQS	Strain Direction	Yield Strength (Ksi)	Ultimate Tensile Strength (Ksi)
1	70.7	Parallel	54.8	65.2
2	69.2	Parallel	54.7	62.5*
3	52.8	Perpendicular	56.6	65.2
4	60.6	Perpendicular	57.0	66.1
5	60.9	Perpendicular	56.2	72.7
6	63.3	Perpendicular	51.7	73.3
7	50.8	Perpendicular	58.5	66.2*
8	57.1	Perpendicular	61.3	66.1
9	51.1	Perpendicular	56.2	64.6

*Failed very near edge of test area
Six test specimens failed outside the test area

TABLE 29. RAIN EROSION DATA FOR SUPRAL 220 CLAD

1 INCH/HOUR SIMULATED RAINFALL (1.8 MM DROPS)

Specimen No.	Velocity (mph)	Impact Angle (o)	Time of Exposure (min)	Comments *
1	500	90	90.0	Surface pitting, increased roughness, increased crater depth.
2	500	90	90.0	Surface pitting, increased roughness, increased crater depth.
3	500	90	180.0	Surface pitting, increased roughness, increased crater depth.
4	500	90	180.0	Surface pitting, increased roughness, increased crater depth.
5	500	90	60.0	Surface pitting and delamination.
6	500	90	60.0	Surface pitting

*Data provided by University of Dayton Research Institute

Tables 30-1 through 30-3 show the results of the chemical processing studies. The specimens were rated on an arbitrary scale of 1 through 10 with 10 being the highest rating or the specimen with little or no corrosion pitting. The specimens, which were selected from nacelle lips, were chemically milled on the inside or concave surface. The chemical milling removes the cladding from the Supral 150 and 220 alloys. Therefore, the chem-milled Supral 150 is identical to the chem-milled Supral 100. The sulphuric acid anodized-dichromate seal specimens received the best overall rating and therefore, based on these tests, this would be the recommended corrosion treatment for the Supral alloys. The clad alloys were superior to the bare alloys in the chemical conversion coated specimens (with deoxidation and without deoxidation) when exposed to 168 hours in the environmental chamber.

2.3.5.2 Chemical Milling

Several samples of Supral 150 and 220 were chemically milled in sodium hydroxide based solution. The channel and the boundary from milled to unmilled areas were examined. Roughness measurements were made using a profilometer and the results are presented in Table 31. The Supral 220 bare was rated the best; however, it was also the only bare alloy evaluated.

2.3.5.3 Spot Welding

A weld schedule was determined, for Supral 150, which satisfies the weld quality, weld nugget diameter, penetration and shear value requirements of Military Specification MIL-W-6858 entitled, "Welding, Resistance, Aluminum, Magnesium, Non-Hardening Steels, Spot and Seam." Certification for production resistance spot welding of this alloy will require experimental refinement of the schedule. The schedule is shown in Table 32.

The Supral 150 welded comparably to standard U. S. aircraft aluminum alloys.

2.3.5.4 Fusion Welding

Supral 150 was evaluated under three conditions A, B and C (see Section 2.2.6.4). The fusion welded discs were X-rayed and there was no significant defect detected which would reflect on the weldability of Supral 150. The fusion-welded specimens were cross sectioned, metallographically prepared and etched. Figures 29, 30 and 31 reveal the differences in grain size and Figures 32, 33 and 34 present the hardness values for the three conditions.

Transverse tensile tests were performed and results are presented in Table 33. Two types of tensile tests were performed. In one case, the weld was left intact; in the other case, the weld crown was filed down. Condition A (weld intact) had the highest tensile properties.

TABLE 30-1. SULPHURIC ACID ANODIZE-DICHROMATE SEAL ENVIRONMENTAL EXPOSURE SALT FOG, 336 HOURS

Supral Alloy	Specimen Number	Inhibited or Caustic Cleaner (1)	Deoxidizer AMCHEM 414 or None	Finish (2)	Salt-Fog Rating	
					Convex (3) Surface	Concave(4) Surface
100	1H	1C	414	SAS	9	10
150	A2H	1C	414	SAS	10	10
	B3H	1C	414	SAS	9	10
	B6H	1C	414	SAS	10	10
	C6F	1C	414	SAS	10	7
220	B3H	1C	414	SAS	10	10
	B6H	1C	414	SAS	10	9

TABLE 30-2. CHEMICAL CONVERSION COATING - NO DEOXIDATION - ENVIRONMENTAL EXPOSURE - SALT FOG, 168 HOURS

Supral Alloy	Specimen Number	Inhibited or Caustic Cleaner (1)	Deoxidizer AMCHEM 414 or None	Finish (2)	Salt-Fog Rating	
					Convex (3) Surface	Concave(4) Surface
100	3H	CC	None	CF	8	7
150	A6H	CC	None	CF	10	8
220	A5F	CC	None	CF	10	7

(1) Turco 4215S or AMCHEM Ridolene 53
(2) C.F.-Chemical Film Alodine 1200) S.A.S.-Sulfuric Anodize + Dichromate-Seal
(3) Clad on Supral 150 and 220
(4) Cladding removed by chem-milling

TABLE 30-3. CHEMICAL CONVERSION COATING WITH DEOXIDATION
ENVIRONMENTAL EXPOSURE - SALT FOG, 168 HOURS

Supral Alloy	Specimen Number	Inhibited or Caustic Cleaner (1)	Deoxidizer AMCHEM 414 or None	Finish (2)	Salt-Fog Rating	
					Convex (3) Surface	Concave (4) Surface
100	2H	1C	414	CF	10	10
	4H	1C	414	CF	7	7
	6H	1C	414	CF	9	10
150	B2H	1C	414	CF	8	10
	A3H	1C	414	CF	10	7
	A4H	1C	414	CF	10	8
	C5F	1C	414	CF	10	8
220	A4F	1C	414	CF	10	5
	A6F	1C	414	CF	10	10
	B1H	1C	414	CF	10	2
	B2H	1C	414	CF	10	10
	B5H	1C	414	CF	10	7

(1) Turco 4215S or AMCHEM Ridolene 53
(2) C.F. - Chemical Film (Alodine 1200) S.A.S. - Sulfuric Anodize + Dichromate-Seal
(3) Clad on Supral 150 and 220
(4) Cladding removed by chem-milling

TABLE 31. EVALUATION OF CHEMICALLY-MILLED SUPRAL ALLOYS

Alloy	Thickness Reduction (%)	RHR* of Chem-Milled Surface	RHR* of Non-Chem-Milled Surface	Comments
Supral 150-T6	51.1	50-60	10-20	The channel is stepped
Supral 150 (As Formed)	61.5	70-80	20-30	Channel is good
Supral 220-T6 Clad	56.4	50-60	15-20	Poor edge definition between milled and unmilled material
Supral 220-T6 Bare	52.5	40-50	10-20	Channel is very good

* Roughness-to-Height Ratio

Fairchild Specification, A-F201, allows a maximum RHR measurement of 160 for Type 1 (sodium hydroxide based) solution.

TABLE 32. RESISTANCE SPOT WELDING - SUPRAL 150

Material:	SUPRAL 150
Lot Numbers: (Spec. Supplied)	29291 (6) 38083 (7)
Gage:	0.040" ± 0.003"
Cleaning Procedure:	Solvent Degrease and Wire Brush
Spot Weld Machine:	Sciaky - FRC No. 54 3-Phase Parallel Hookup
Spot Weld Parameters:	Sciaky Controls
Pressure Weld (psi):	25/17 Var. Cycle
Weld Heat Time:	2 Cycles Phase 45%
Cool Cycle:	3 Weld Imp. 1
Current Decay:	6 Cycles Phase 20%
Forge Initiation:	Weld, Cool, 2.8
Electrodes:	Upper 10"R, 5/8"D
	Lower 10"R, 5/8"D
Shear Value (average)	800 Lb.

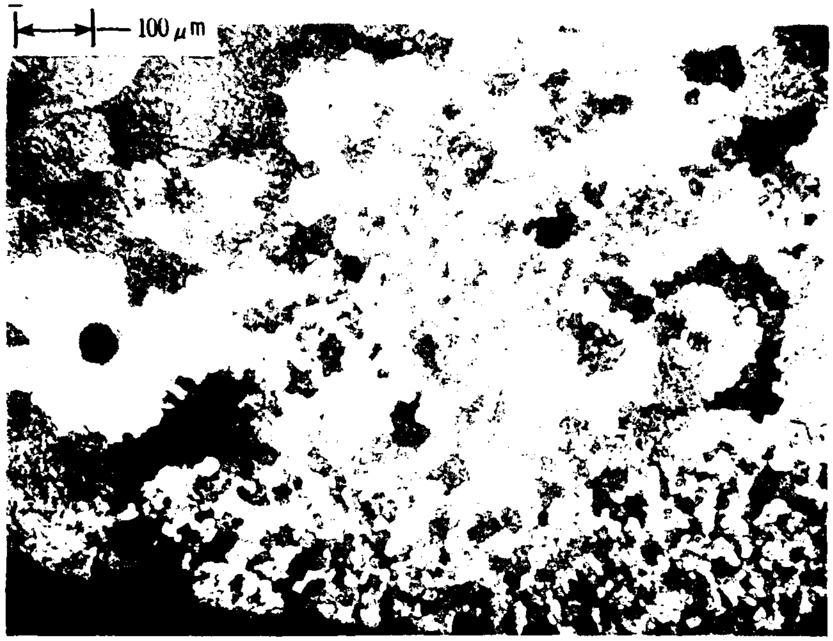

Figure 29. Condition A - Grain Size Near Center of Weld 100X

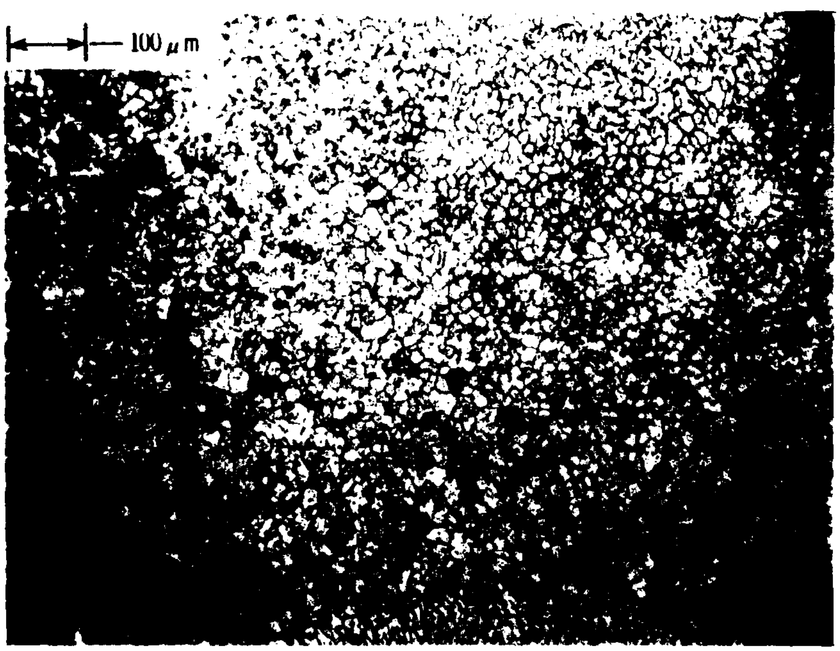

Figure 30. Condition B - Grain Size Near Center of Weld 100X

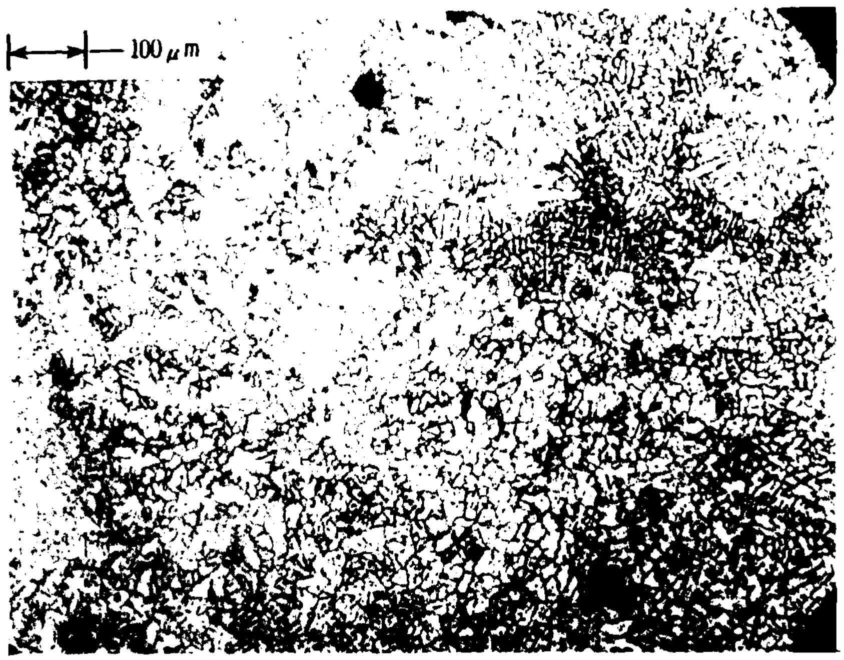

Figure 31. Condition C - Grain Size Near Center of Weld 100X

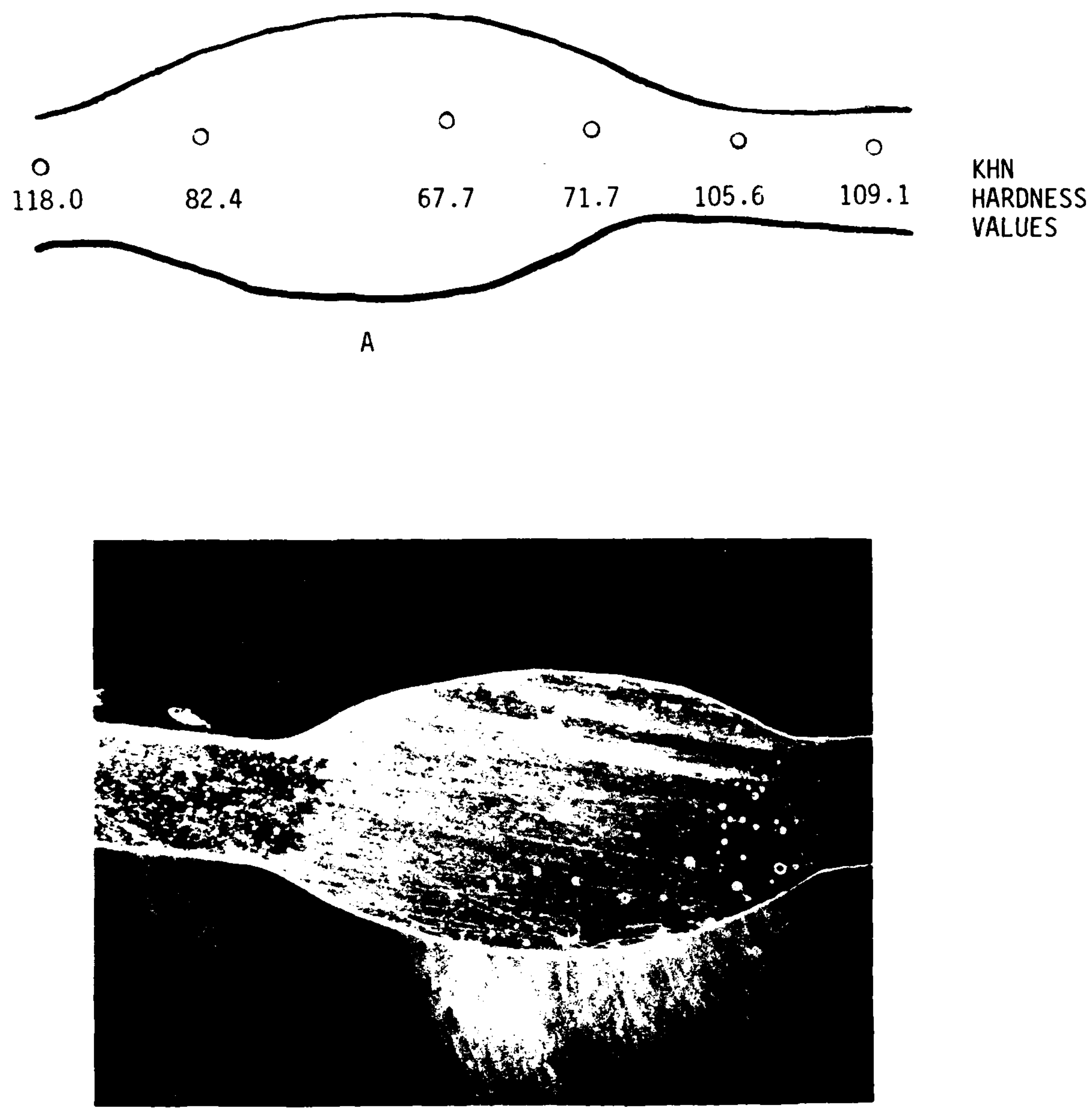

Figure 32. Fusion Welded Specimen with Knoop Hardness Values - Condition A 15X

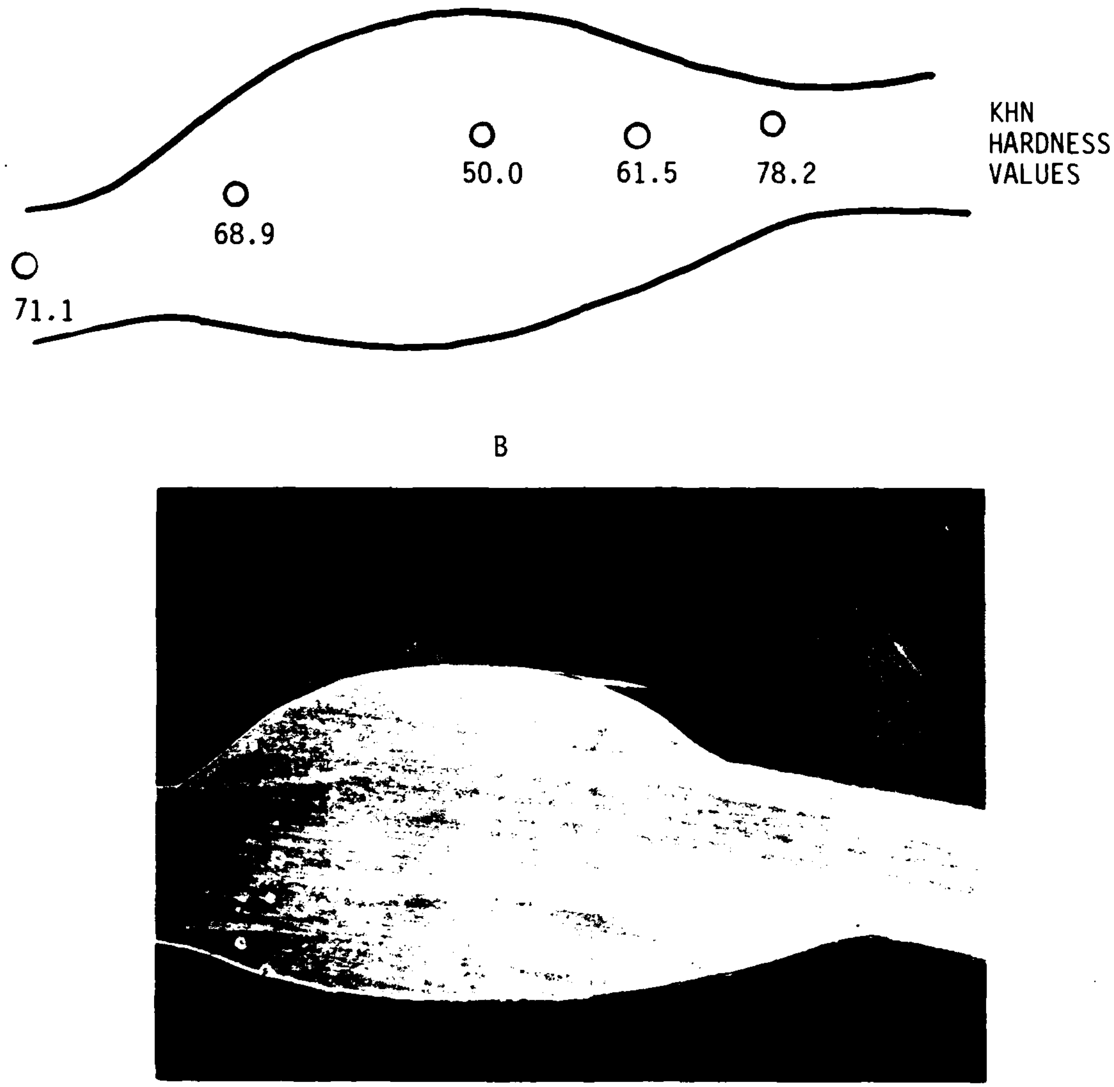

Figure 33. Fusion Welded Specimen with Knoop Hardness Values - Condition B 15X

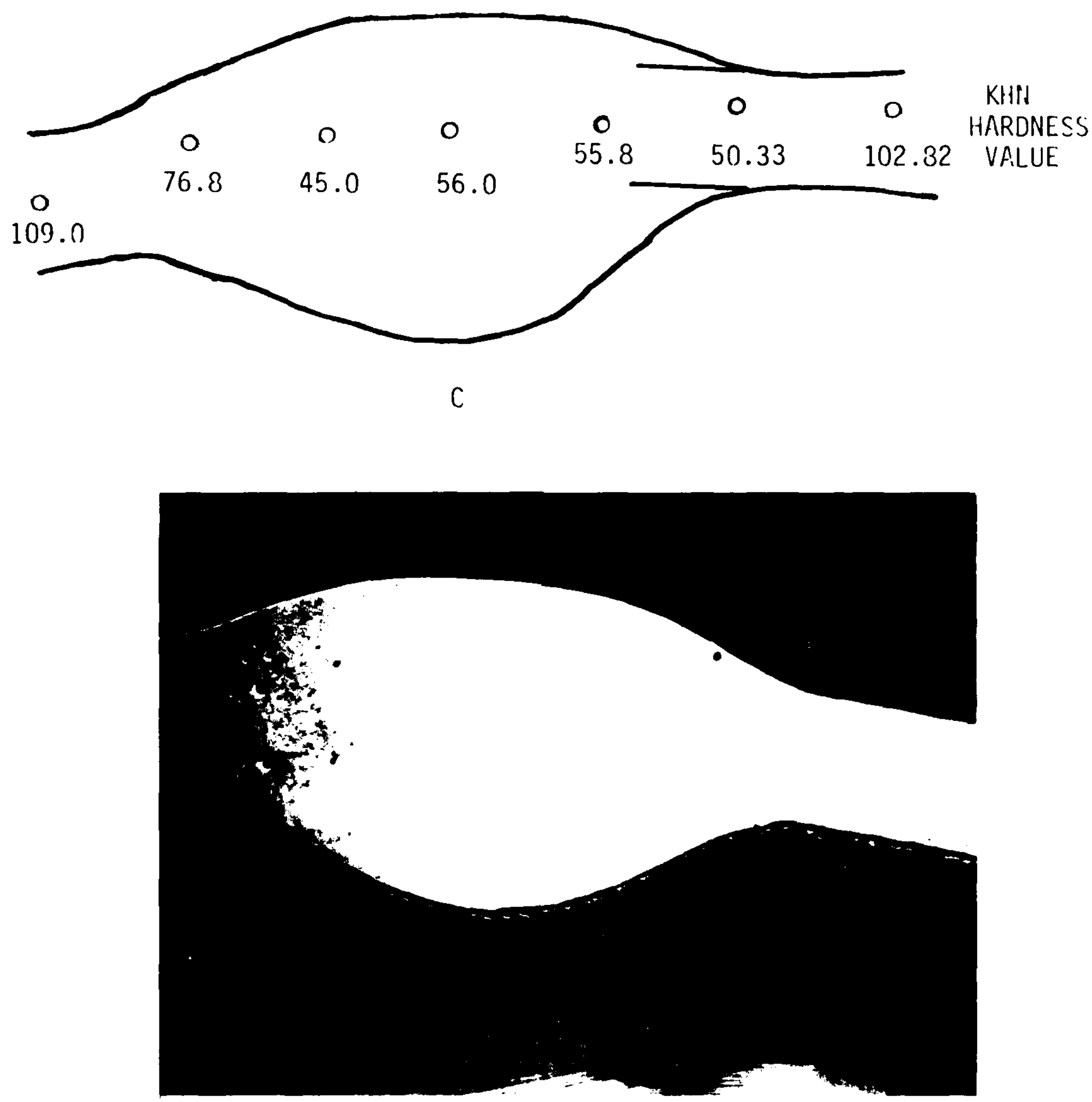

Figure 34. Fusion Welded Specimen with Knoop Hardness Values - Condition C 15X

TABLE 33. FUSION WELDED (TRANSVERSE TENSILE) TEST RESULTS

Specimen No.	Weld Crown Intact (2) or Filed (3) Smooth	Weld (4) Condition	Yield Strength 0.2% Offset	Ultimate Strength (ksi)
B39-5	Filed	A	23.2	33.8
B39-6	Filed	A	(1)	26.2
B39-7	Filed	A	22.4	29.3
B39-3	Intact	A	37.7	51.9
B39-8	Intact	A	37.1	47.7
B39-9	Intact	A	35.0	48.1
B38-2	Filed	B	22.5	29.4
B38-4	Filed	B	20.4	25.5
B38-6	Filed	B	20.9	26.8
B38-1	Intact	B	18.0	36.0
B38-2	Intact	B	19.2	34.4
B38-5	Intact	B	19.2	34.0
B37-2	Filed	C	(1)	25.1
B37-7	Filed	C	(1)	25.3
B37-9	Filed	C	(1)	26.0
B37-1	Intact	C	22.7	38.4
B37-3	Intact	C	26.7	38.8
B37-8	Intact	C	24.4	36.9

(1) Failed prior to yield at 0.2% offset
(2) Thickness measurement made adjacent to crown
(3) The weld has been ground flat
(4) See Paragraph 2.2.6.4

Note: The weld rod was the British equivalent of U.S.4043.

2.3.5.5 Fastener Allowables

Fastener allowable tests were performed on Supral 150 material utilizing a lap joint shear specimen. The test was conducted in accordance with MIL-STD-1312 Method 4A. Three different International Brazier Head fastener sizes were tested (1/8, 5/32 and 3/16-inch diameters). The test results are presented in Table 34.

2.3.5.6 Ultrasonic Welding/Weldbonding

Due to limited contract funding, the following effort was performed in conjunction with an FRC-supported research study. Since ultrasonic welding/ weldbonding is a technically advanced manufacturing process, it is important to report all results obtained.

In anticipation of assembling SPF structures with a low-cost welding process, work has proceeded to qualify ultrasonic spotwelding and ultrasonic weldbonding with the Supral 220 alloy.

Work was performed to establish tools and process schedules on the ultrasonic welder. Single spotwelds are made on overlapping 2 by 4-inch pieces and are pulled to failure in a test machine to establish spot strengths. Parameters such as weld tip radius, clamping pressure, pressure rise rates and ultrasonic power rise rates, tool temperature, frequency and welding time are varied to establish a satisfactory spot strength and spot consistency. This effort resulted in a schedule which will produce spot strengths of 2500 pounds for the alloy/thickness case at hand when welding with or without an adhesive film interlayer.

For the large panel tests, Supral 220 material (0.090-inch thick, clad both sides) was received from Superform in the pseudo-formed* condition. It was then treated to the T6 condition and thinned to 0.045-inch thickness by chem-milling. Panel sections, 30 by 12 inches were cut and two 1/4-inch thick doubler plates were bonded on one end of each panel. Holes, 1 1/4-inch diameter, were drilled through the doubled ends to accommodate pins for end loading of the test joints.

Large panel single overlap test joints were made by overlapping two panels to the extent of 4 inches. In all cases, the chem-milled surfaces were mated leaving the alclad surfaces on the exterior. Uniformly in the overlap, spotwelds were made in two rows along the lines separated by 2 inches. The welds varied in numbers but were always equally spaced within the rows.

Five large panels have been tested. Three were without an adhesive interlayer but were welded with a proprietary welding aid in the interface. Two other joints were weldbonded with the faying surfaces prepared by FPL etching and coating with the adhesive primer BR-127 (American Cyanamid). Welding was done through an 0.005-inch thick film adhesive FM-123 (American Cyanamid). After welding the joint, it was cured in an oven at 250°F. Results of lap shear tests are presented in Table 35.

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*Supral material which has not been strained but receives the same temperature and time exposure as superplastically formed sheet.

TABLE 34. FASTENER ALLOWABLE TEST RESULTS
SUPRAL 150 - T6 CONDITION

Specimen No.	Rivet Diameter	Yield Shear Stress (psi)	Ultimate Shear Stress (psi)	Type of Failure
D4-1	1/8	40650	46341	Fastener Shear
D4-2	1/8	40650	47967	Fastener Shear
D4-3	1/8	39837	46341	Fastener Shear
D4-4	1/8	39837	46341	Fastener Shear
Mean		40.2 ± 0.4 (Ksi)	46.7 ± 0.7 (Ksi)	
D5-1	5/32	36458	44270	Fastener Shear
D5-2	5/32	36980	42708	Fastener Shear
D5-3	5/32	39062	44167	Fastener Shear
D5-4	5/32	39062	42292	Fastener Shear
Mean		37.9 ± 1.2 (Ksi)	43.4 ± 0.9 (Ksi)	
D6-1	3/16	39130	43841	Fastener Shear
D6-2	3/16	35144	44930	Material Tear Out
D6-3	3/16	36232	43841	Fastener Shear
D6-4	3/16	34783	43480	Fastener Shear
Mean		36.3 ± 1.7 (Ksi)	44.0 ± 0.54 (Ksi)	

Notes: International Brazier Head/MS 20470-D4
Supral 150 Thickness = 0.060 - 0.070 inch

TABLE 35. ULTRASONIC WELDED JOINTS LAP SHEAR TEST RESULTS

Joint Design	Sheet Stress at Failure	Failure Mode
6 spots - no adhesive	17,800 psi	Joint sheared
10 spots - no adhesive	29,200 psi	Joint sheared
16 spots - no adhesive	44,000 psi	Joint sheared
22 spots - no adhesive	47,800 psi	Sheet tore outside the joint
6 spots - with adhesive	55,000 psi	Sheet failed outside joint
12 spots - with adhesive	60,000 psi	Sheet failed outside joint

Figure 35 is a plot of sheet failing stress against the number of ultrasonic welds in the joint. As is typically seen with this type of joint, there is an additive slope where joint strength is the sum of the number of spots in the joint, up to the yield strength of the material; and then there follows a shallower slope as joint strength rises towards the sheet ultimate strength. As indicated in the plot, the additive slope will have failures in or around the spots, while above the yield stress failures occur by sheet tearing along the spot rows or near the end doublers.

2.3.5.7 Adhesive Bonding

The superplastically formed (SPF) Supral 150 clad aluminum alloys were investigated for the applicability of the adhesive bonding. Results showed average static lap shear strength of 4087 psi and 3865 psi for the following surface treatments: the optimized FPL etch and the PABST** phosphoric acid anodize, respectively. The adhesive system used was the FM-73M 0.06 psf* OST manufactured by American Cyanamid Company. Average bondline thickness of 4 mils was observed. Scanning electron microscope (SEM) analysis on 90° bent specimens was used to determine the thickness of the oxide layer and to provide assurance that the proper surface treatment was achieved. The SEM samples were processed at the same time as the test panels. The oxide thicknesses for the two surface treatments were approximately 300Å and 10,000Å for the optimized FPL*** etch and the PABST phosphoric acid anodize, respectively. The results of the wedge crack test using phosphoric acid anodize and FPL etch optimized etch are listed in Tables 36 and 37, respectively.

Wedge crack specimens were exposed to 95-100% relative humidity at 120°F. The crack growth was measured after 1 hour exposure and then remeasured after 3 hours and 16 hours of exposure. 100% cohesive failure was observed on both the lap shear and wedge crack specimens.

The lap shear strength and wedge crack growth data were typical of aluminum alloys in the 2XXX and 7XXX series.

2.3.5.8 Weldbonding

Lap shear tests were performed on adhesively weldbonded Supral 150 specimen panels. The lap joint bonds were accomplished by both weldbonding and B.F. Goodrich A-1444B adhesive. All tests were performed at ambient conditions.

The results of the lap shear test are presented in Table 38. The majority of the specimen failures occurred in the aluminum adherends as opposed to the lap joint. Three specimens exhibited clean lap joint failures with one of these specimens possessing misaligned lap joint panels. Two specimens failed partially at the lap joint and partially in the aluminum.

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* OST - one side tacky
** Primary Adhesively Bonded Structure Technology
*** Forest Product Laboratory

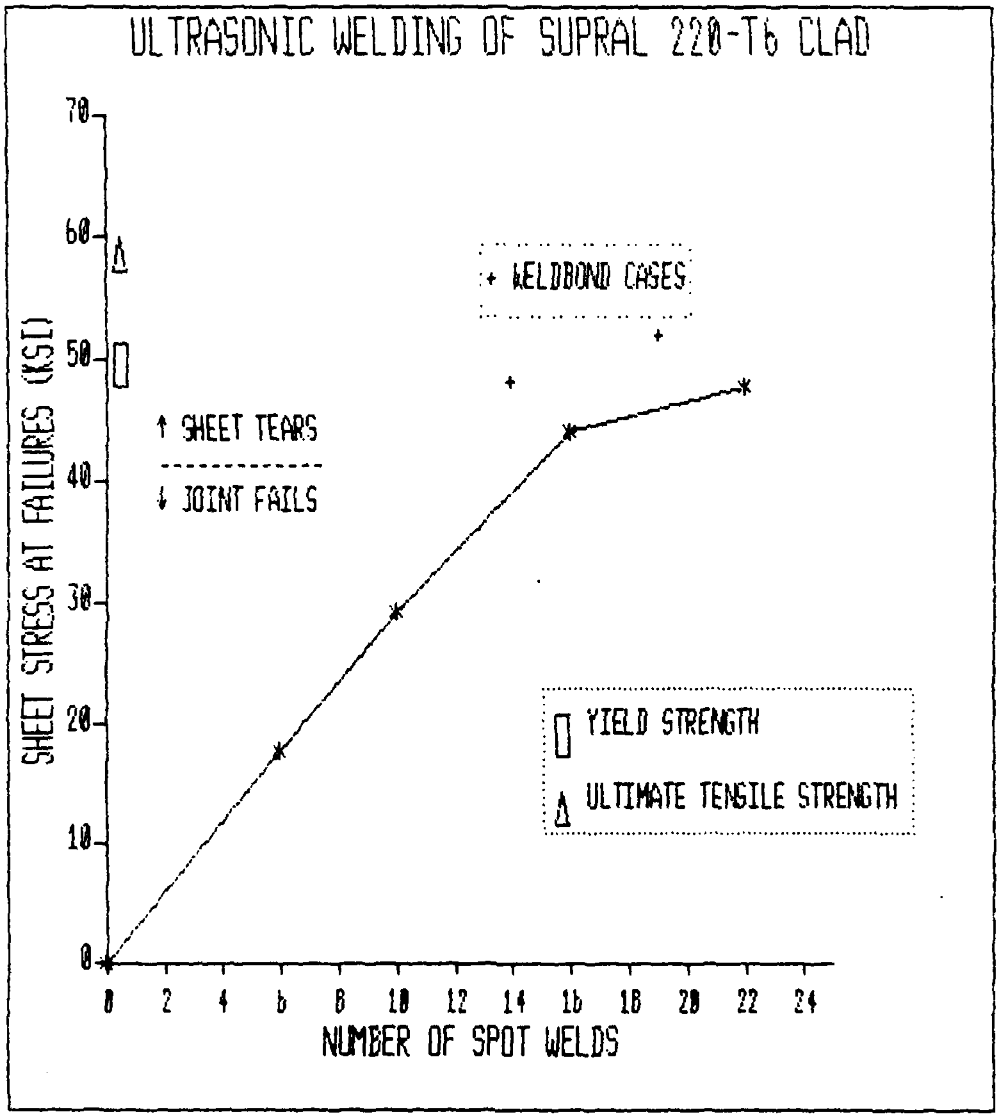

Figure 35. Ultrasonic Welding of Supral 220 Clad

TABLE 36. WEDGE CRACK DATA - 95-100% RELATIVE HUMIDITY EXPOSURE AT 120°F - SUPRAL 150 CLAD/SUPRAL 150 CLAD - PABST SYSTEM

Specimen Code	Bondline Thickness (mils)	Wedge Crack Growth (inches)			Failure
		1 Hour	3 Hours	16 Hours	
W1	4.1	0.030	0.038	0.038	100% cohesive
W2	3.5	0.020	0.030	0.030	
W3	4.5	0.048	0.058	0.058	
W4	3.1	0.008	0.008	0.008	
W5	3.8	0.015	0.035	0.035	
	Average	0.024	0.034	0.034	

Adhesive System: 15-Volt Phosphoric Acid Anodize/BR127 Primer/ FM 73M 0.06 psf OST

Exposure Started: 8 August 1983

Note: Fairchild Republic Specification A-F502 allows crack growth of no more than 0.05 inch after 1-hour exposure at 95-100% RH and 120°F.

TABLE 37. WEDGE CRACK DATA - 95-100% RELATIVE HUMIDITY EXPOSURE AT 120°F - SUPRAL 150 CLAD/SUPRAL 150 CLAD - OPTIMIZED FPL ETCH

Specimen Code	Bondline Thickness (mils)	(Wedge Crack Growth (inches)			Failure
		1 Hour	3 Hours	16 Hours	
W1	5.53	0.010	0.010	0.010	100% cohesive
W2	5.50	0.075	0.125	0.185	
W3	5.25	0.075	0.155	0.170	
W4	5.80	0.075	0.100	0.173	
W5	5.00	0.095	0.140	0.255	
Average		0.066	0.106	0.159	

Adhesive System BR127 Primer/FM73M 0.06 psf OST Adhesive
Optimized FPL Etch (Sulfuric Acid/Sodium Dichromate)

Exposure Started: 15 August 1983

TABLE 38. SPF ALUMINUM DOUBLE LAP SHEAR TEST RESULTS

SUPRAL 150-T6 CLAD

Specimen	Lap Shear Area ($in.^2$)	Failure Load (lb_f)	Lap Shear Stress (psi)	Notes
A	1.051	2475	2355	1
B	1.041	2490	2392	1, 2
C	1.057	2800	2649	3
D	1.066	2830	2655	4
E	1.011	2720	2690	4
H	1.028	2340	2276	1
J	1.053	2125	2018	4
K	0.961	2150	2237	3
L	1.049	2525	2407	4
M	1.019	2550	2502	4
O	1.052	1970	1873	4
R	1.035	2500	2415	4
S	0.988	2200	2227	4
T	1.036	1985	1916	4
U	0.975	2540	2605	4

Notes:

1) Adhesive Lap Joint Failure
2) Specimen Lap Joint Adherends Misaligned
3) Partial Lap Joint - Partial Aluminum Failure
4) Aluminum Failure

SECTION III

TASK B - MATERIAL EVALUATION OF SUPRAL 220

3.1 OBJECTIVE

The objective of Task B was to supplement Supral 220 test data previously obtained in Task A. The Task B tests evaluated notch tensile and fatigue data important to design of primary structures. These test results will help determine if Supral 220 is competitive with the superplastic 7475 alloys in terms of mechanical properties.

3.2 APPROACH

In Task B, Fairchild conducted tests on the Supral 220 alloy as described in paragraphs 2.2.1-2.2.5. Table 39 shows the type of property test and the number of tests performed.

3.3 RESULTS

3.3.1 Tension - Sharp Notched - K_T=16

Tests were conducted on sharp notched tensile specimens and the results are presented in Table 40. As has been noted previously, the tensile properties decreased when the EQS was greater than 150%.

3.3.2 Tension at a Temperature = -65°F

Tests were performed on smooth (K_T=1) tensile specimens at a temperature of -65°F. The results in Table 41 indicate that subzero temperature tensile tests are similar to ambient tensile tests. Here too, there are tensile failures in the high equivalent strain range, where the specimens failed without yielding. Figure 36 relates the properties to the respective equivalent strains.

3.3.3 Tension - Notched at a Temperature = -65°F

Notched (K_T=3) tensile tests were conducted at a temperature =-65°F. The results, presented in Table 42, are approximately 15% greater than the ambient temperature K_T=3 results. Figure 37 shows the relationship between the notched tensile strength and the EQS.

3.3.4 Tension at a Temperature = +210°F

Smooth (K_T=1) tensile specimens were tested at a temperature = 210°F. The results, presented in Table 43,indicate that the elevated test results are slightly lower than the room temperature results. Figure 38 relates the tensile properties to the respective EQS.

TABLE 39. TEST MATRIX TASK B

SUPRAL 220
NACELLE LIP AND DISC MATERIAL

Test Procedures Description	Number of Test Specimens
Tension; Sharp Notched (K_T = 16)	35
Tension; Smooth (K_T = 1) -65^{o}F	35
Tension; Notched (K_T = 3) -65^{o}F	35
Tension; Smooth, (K_T = 1) 210^{o}F	35
Fatigue; Smooth (K_T = 1) Perpendicular to Strain	40
Fatigue; Notched (K_T = 3) Perpendicular to Strain	40
Electrical Conductivity	35
Corrosion (Salt Spray)	15

TABLE 40. AVERAGE SHARP NOTCHED TENSILE PROPERTIES AT K_T=16

ALLOY SUPRAL 220-T6 CLAD

Condition	EQS Range	NTS, Ksi		NTS/Fty	NTS/Ftu
		$\bar{X}$	σ_{n-1}		
Parallel to Strain	Low	53.0	2.5	1.040	0.882
	Medium	50.1	2.9	1.000	0.885
	High	41.9	3.6	0.871	0.810
Perpendicular to Strain	Low	50.6	1.9	0.962	0.825
	Medium	48.6	4.2	0.959	0.814
	High	43.0	4.4	0.905	0.855
Perpendicular and Parallel to Strain	Low	51.7	2.4	1.000	0.853
	Medium	49.4	3.5	0.980	0.834
	High	42.4	3.9	0.889	0.833

TABLE 41. AVERAGE TENSILE PROPERTIES AT -65^{O}F (K_T=1)

ALLOY SUPRAL 220-T6 CLAD

Condition	EQS Range	Fty, Ksi		Ftu, Ksi		Elong. % in 2"	
		$\bar{X}$	σ_{n-1}	$\bar{X}$	σ_{n-1}	$\bar{X}$	σ_{n-1}
Parallel to Strain	Low	52.5	3.2	61.9	4.0	7.1	2.0
	Medium	55.0	1.8	64.9	1.9	7.3	0.7
	High	47.4	1.2	53.3	2.6	3.0	1.0
	High	-	-	-	-	-	-
Perpendicular to Strain	Low	50.6	1.1	57.2	5.7	4.4	2.0
	Medium	53.5	1.2	61.5	3.6	5.4	2.7
	High	(1)		28.8	1.6	0	0
	High	-	-	-	-	-	-
Perpendicular and Parallel to Strain	Low	51.6	2.5	59.5	5.3	5.7	2.4
	Medium	54.2	1.6	63.1	3.3	6.3	2.2
	High	47.4	1.2	(2)		0	0
	High					3.0	1.0

Notes:

(1) Specimen failed prior to 0.2% yield

(2) Though parallel-high and perpendicular-high specimens are all between 150-250% EQS, the perpendicular-high specimens were between 210-250%, while the parallel high specimens were between 160-200% EQS. This explains the difference in results between the perpendicular and parallel high strain specimens.

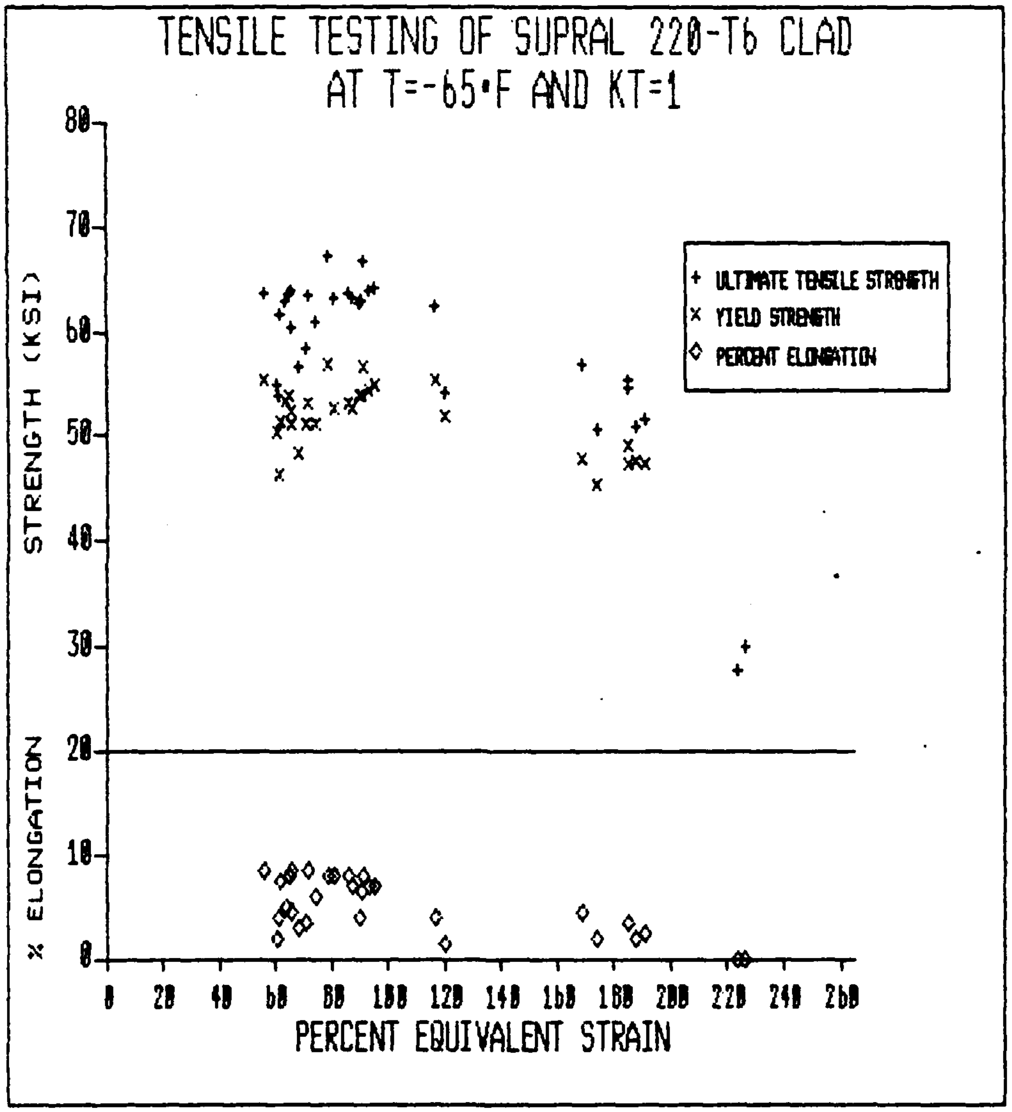

Figure 36. Tensile Properties of Supral 220-T6 Clad at $T=-65^{O}F$ ($K_T=1$) versus EQS

(Each point denotes a test result)

TABLE 42. AVERAGE NOTCHED TENSILE STRENGTH AT T=-65^{O}F (K_T=3)

ALLOY SUPRAL 220-T6 CLAD

Condition	EQS Range	NTS, Ksi		NTS/Fty	NTS/Ftu
		$\bar{X}$	σ n-1		
Parallel to Strain	Low	62.8	0.7	1.196	1.015
	Medium	57.5	4.8	1.045	0.886
	High(1)	48.5	5.1	1.023	0.910
Perpendicular to Strain	Low	60.8	0.4	1.202	1.063
	Medium	58.4	3.0	1.092	0.950
	High(1)	26.9	3.1	(3)	0.934
Perpendicular and Parallel to Strain	Low	61.8	1.2	1.193	1.018
	Medium	58.0	3.9	1.151	0.980
	High	(2)		(2)	(2)

(1) Though parallel-high and perpendicular-high specimens are all between 150-250% EQS, the perpendicular-high specimens were between 210-250% while the parallel-high specimens were between 160-200%. For this reason, the parallel and perpendicular high specimens differ so greatly.

(2) The parallel and perpendicular values vary too much to calculate together.

(3) Unable to calculate due to failure prior to yield strength.

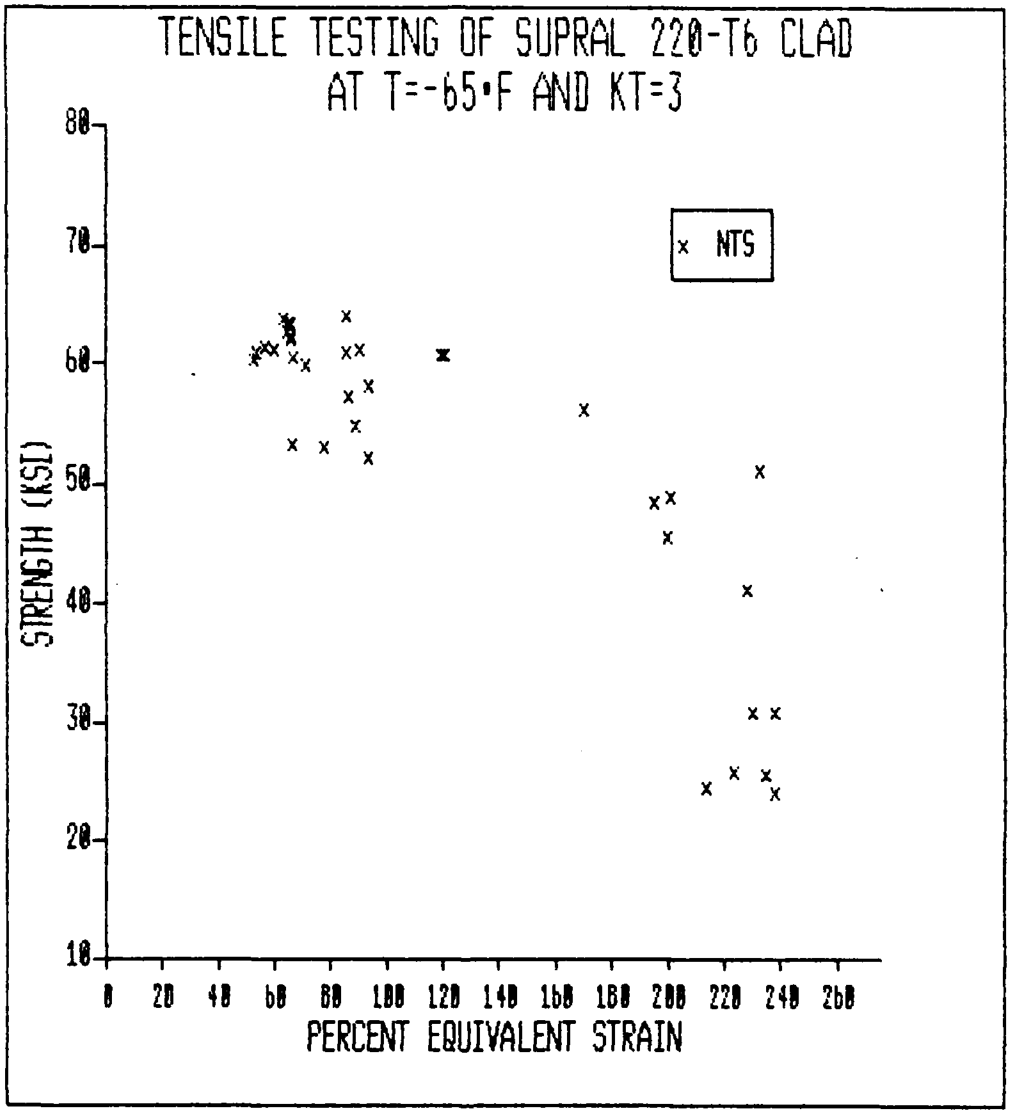

Figure 37. Tensile Strength of Supral 220-T6 Clad at T=-65^{O}F (K_T=3) versus EQS
(Each point denotes a test result)

TABLE 43. AVERAGE TENSILE PROPERTIES AT 210°F (K_T=1)

ALLOY SUPRAL 220-T6 CLAD

Condition	EQS Range	Fty, Ksi		Ftu, Ksi		Elongation % in 2"	
		$\bar{X}$	σ_{n-1}	$\bar{X}$	σ_{n-1}	$\bar{X}$	σ_{n-1}
Parallel to Strain	Low	48.3	0.3	54.5	2.4	10.5	1.0
	Medium	49.0	1.9	56.2	1.0	7.4	1.2
	High[4]	43.2[1]	1.8	39.8[2]	0.6	1.9[2]	0.5
	High	-		46.0[3]	2.7	1.0[3]	0
Perpendicular to Strain	Low	47.6	0.6	54.8	0.9	8.2	2.7
	Medium	47.9	1.0	54.9	1.0	6.7	0.4
	High	[2]		35.1[2]	6.9	1.0[2]	0
Perpendicular and Parallel to Strain	Low	48.0	0.6	54.7	1.7	9.1	2.4
	Medium	48.5	1.6	55.5	1.2	7.1	0.9
	High	43.2		37.4[2]	4.8	1.3	
	High	-		46.0[3]	2.7		

1. Some (or all) of the test specimens failed prior to 0.2% offset yield. These values are listed separately.
2. Values for specimens which failed prior to 0.2% offset yield (all of the perpendicular-high and 33% of the parallel-high).
3. Value for specimens which failed after the 0.2% offset yield.
4. Though parallel-high and perpendicular-high specimens are all between 150-250% EQS, the perpendicular-high specimens were between 210-250% while the parallel high specimens were between 160-200%.

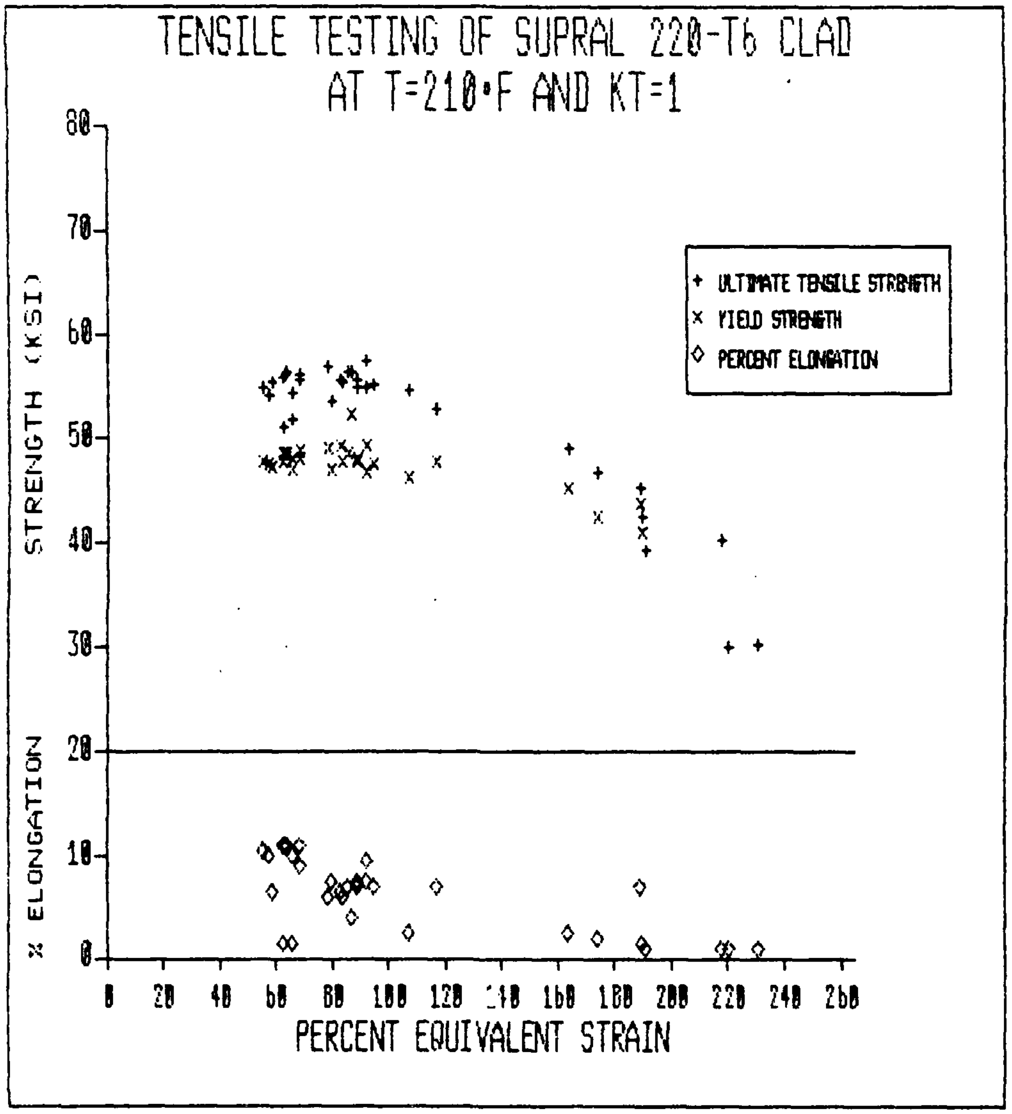

Figure 38. Tensile Properties of Supral 220 - T6 Clad at T=210^{O}F (K_T=1) versus EQS

(Each point denotes a test result)

3.3.5 Fatigue - Parallel to Strain

Smooth (K_T=1) specimens were fatigue tested. The results (Figure 39) are similar to the perpendicular to strain results. The high EQS range test specimens showed failures at less cycles than the medium and low EQS range specimens.

3.3.6 Fatigue - Notched - Perpendicular to Strain

Notched (K_T=3) specimens were fatigue tested. The S-N curves (Figure 40) for the low, medium and high equivalent strain range specimens were identical. This fact was also noted in the parallel to strain K_T=3 test specimens.

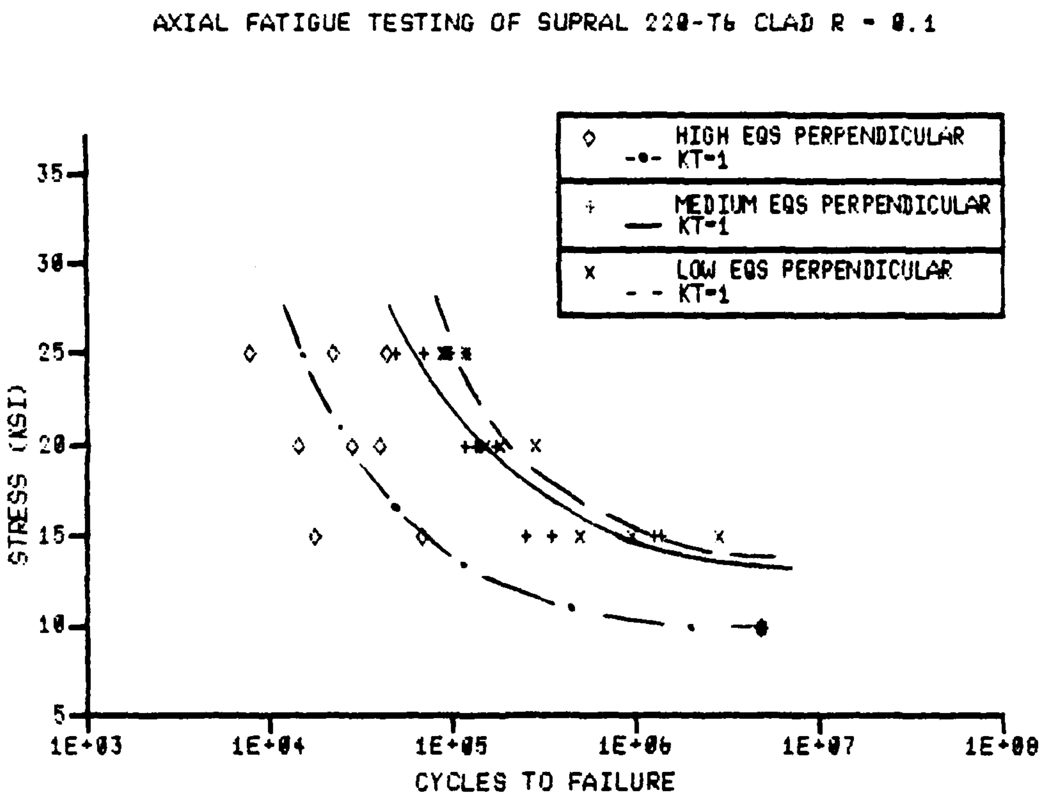

Figure 39. Fatigue Properties of Smooth Specimens, Perpendicular to Strain - Supral 220-T6 Clad

(Each point denotes a test result)

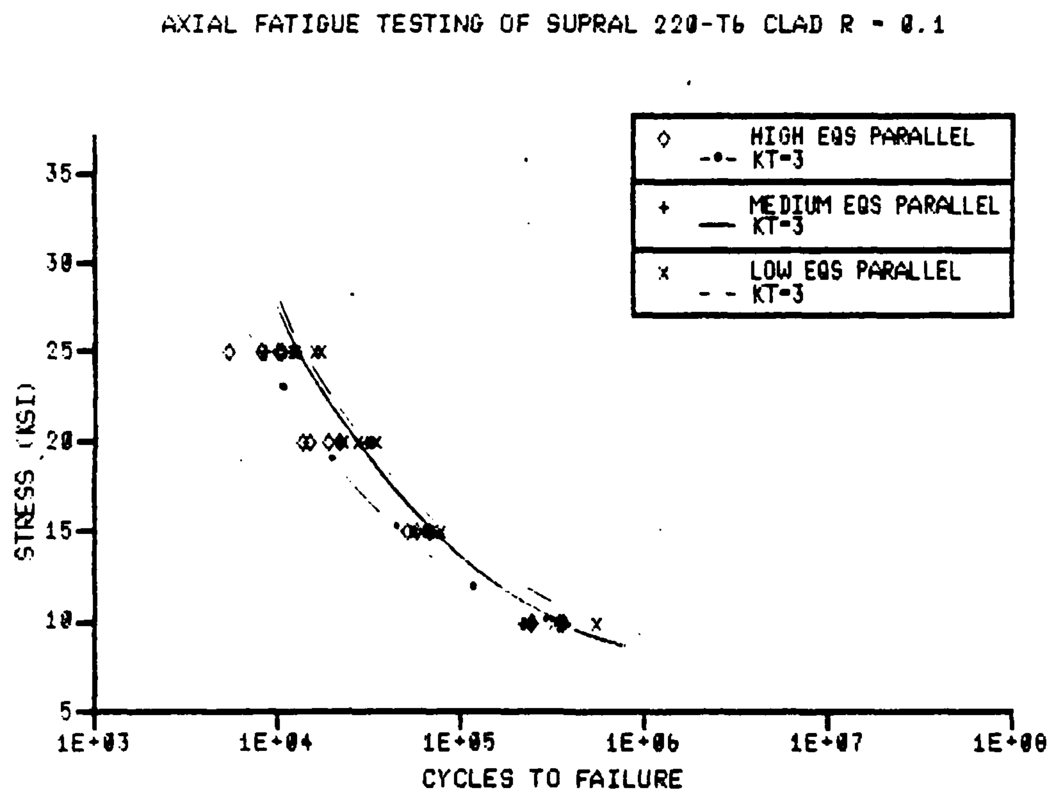

Figure 40. Axial Fatigue Properties of Notched Specimens, Parallel to Strain - Supral 220-T6 Clad

(Each point denotes a test result)

SECTION IV

SUMMARY OF PROPERTY EVALUATIONS

4.1 GENERAL

Under this contract, many of the mechanical, physical and corrosion properties of the superplastic Supral alloys 100, 150 and 220 clad have been evaluated. When the evaluation commenced, the three Supral alloys were new to the United States aircraft industry. The alloys had been used on a very limited basis and very little property data was available. Since the evaluation was one of the first, we did not know what trends to expect nor how the properties would change at various strain levels. As the testing proceeded, we began to note several trends and these trends or patterns are summarized in this section. One observation which is generally true amongst many of the mechanical property tests (i.e., all tensions, bare alloy fatigue K_T=1, bearing, compression and hardness) is a significant drop in properties in the high equivalent strain range. We believe that it is in this range that the cavitation has grown to an extent to detrimentally affect the properties.

As has been noted earlier, the purpose of this research is to study the ALCAN/Superform Supral alloys and to determine the feasibility and limits for incorporating these alloys onto the aircraft. In order to determine this, the alloys have been tested under conditions yielding MIL-HDBK-5 data. The properties were obtained with reference to the direction of the superplastic forming strains (perpendicular and parallel) and three equivalent strain regions (high, medium and low).

4.2 MECHANICAL PROPERTY TESTS

4.2.1 Tensile Tests - Supral 100, 150 and 220 Clad (all T6)

- Perpendicular and parallel to strain tests at the same strain level yielded near identical results.
- Most properties decrease as the equivalent strain (i.e., amount of thinning) is increased.
  - There are small differences in properties between the low and medium EQS range test results.
  - The high EQS range specimens have noticeably lower tensile properties. Tensile strengths decrease on the average of 8-23% when comparing from the low to the high strain ranges.
  - Percent elongation decreases greatly in the high equivalent strain range. In many cases the elongation decreases 90-95% to a 1 percent elongation.

- Non-ambient temperature tensile results ($T=-65^{o}F$, $T=210^{o}F$) are similar to room temperature results and show similar trends.
    - The one exception is the yield strength at $210^{o}F$ is slightly lower than the room temperature yield strength.
- Notched tensile properties show the same trends as smooth tensile properties.

4.2.2 Compression Properties - Supral 220-T6 Clad

- Perpendicular and parallel to strain test results are almost identical.
- Unlike other mechanical properties, compression properties increase moderately as the EQS increases in the low and medium EQS range. Properties decrease noticeably after 150% EQS.

4.2.3 Bearing Properties - Supral 220-T6 Clad

- Perpendicular and parallel to strain test results were almost identical.
- The e/D = 1.5 test results indicate a slight increase in properties in the low EQS range.
- The properties decrease significantly in the high equivalent strain range.

4.2.4 Fatigue Properties - Supral 100, 150 and 220 Clad (all T6)

- Cladding significantly decreases the fatigue life of superplastically formed Supral alloys. This is caused by the extremely large grains which grow in the clad metal during the forming operation. The enlarged grains adversely affect the fatigue life of the material. The grains in the base metal remain extremely fine in size.
- Fairchild test results (80 test specimens) indicate no significant difference between parallel and perpendicular fatigue specimens. Air Force test results (12 test specimens) showed a shorter fatigue life in the perpendicular specimens. The failures of the AFWAL/FIBE specimens coincided with surface defects (Reference 6) caused by SPF tooling while the failures of Fairchild Republic specimens were caused primarily by cavitation. The differences in test result cannot fully be explained at this time.
- Smooth fatigue specimen test results show similar S-N curves in the low and medium EQS ranges but lower fatigue life for the high EQS range.
- Fairchild results of Supral 220 unnotched fatigue tests were lower than originally expected by Superform/ALCAN. Further investigation by Superform showed that fatigue failure was initiated from subsurface defects

associated with liquation. Additional investigations on this matter have been reported in Reference 4.

- o Notched specimen Supral 220-T6 clad test results show nearly identical S-N curves in all EQS ranges. Equivalent strain is not effective in the notched fatigue life because of the dominance of the notch on the fatigue initiation.

4.2.5 Crack Propagation Properties - Supral 220-T6 Clad

- o Crack growth rates were somewhat higher than those for 2024-T3 and 6061-T6, but noticeably slower than 7075-T6.

4.2.6 Hardness Values - Supral 220-T6 Clad

- o Hardness values decreased in the high equivalent strain range but are not affected in the low and medium EQS.

4.3 CORROSION PROPERTIES

- o Salt spray test results on Supral alloys are equivalent to conventional aluminum alloys.

- o Supral 220-T6 clad showed excellent stress corrosion resistance by withstanding 48.75 Ksi of constant stress for 30 days of testing (alternate immersion).

- o Supral 220-T6 clad, uncoated rain erosion specimens showed erosion resistance comparable to typical aluminum aircraft alloys.

4.4 METALLOGRAPHY/MICROCAVITATION

- o Metallographic examinations of superplastically formed specimens at varied equivalent strains revealed a uniformly fine grain microstructure.

- o Microcavitation (porosity due to SPF) is the cause of low mechanical properties, particularly in the high equivalent strain range. Major impact appears to be in ductility, reducing percent elongation to an unacceptable value. (Methods to minimize microcavitation are currently being investigated by Superform, Ltd.).

4.5 ELECTRICAL CONDUCTIVITY

- o Supral 220 clad has a slightly higher electroconductivity than Supral 100 and 150. All three alloys are within the range of standard aluminum alloys (i.e., 7475).

- o Measurements from the low and medium EQS range (T6) have identical IACS values while the high EQS range is sometimes slightly lower.

- As SPF-formed but not heat treated test material showed a significant decrease in electroconductivity as the EQS increases.

4.6 MANUFACTURING PROCESSES

- When subject to standard cleaning and surface finishes (alodine, anodize) the corrosion resistance of Supral alloys is similar to conventional aluminum alloys.

- There were no difficulties in chemical milling Supral alloys.

- A resistance spotwelding schedule was developed indicating that Supral 150 gives results comparable to standard aluminum aircraft alloys.

- Supral 150 is a fusion-weldable alloy. X-ray evaluation indicated a fine quality weld.

- The Supral alloys are ultrasonically weldable.

- The results of adhesive bonding Supral 150 showed little crack growth in wedge crack exposure and lap shear strengths equivalent or better than 7075.

- Supral 150 was resistance weldbonded with good quality weld nuggets.

SECTION V

CONCLUSIONS

The investigation of the properties and characteristics of the Supral series of aluminum superplastic alloys has afforded a unique opportunity to evaluate competitive alloys and their importance in United States aircraft technology. The overall conclusions are as follows:

Superplastic forming of Supral aluminum alloys can be a cost benefiting process because of reduction in part and fastener count and because of improved design flexibility. The mechanical properties of the Supral alloys offer a useful range of properties which are applicable for most aircraft designs. In addition, the availability of clad materials permit them to be used for external applications. Standard shop treatments typical for U. S. aluminum aircraft alloys are effective and cleaning, alodining, anodizing, chem-milling, and welding all give satisfactory results with the Suprals.

The data indicates that Supral formability is comparable to that of 7475 SPF alloy (Process E, Rockwell); however, Supral's high strain rate and lower superplastic forming temperature permits a more rapid rate for forming and the use of aluminum forming tooling rather than steel. Cavitation is present in the Supral alloy (as in 7475) but in the United Kingdom, preference is given to controlling cavitation by limiting total strain rather than by the more expensive method of applying back pressure. For this reason, determination of the optimum amount of total strain to maximize properties was made a prominent feature of this contract.

The mechanical property data obtained by Fairchild's IRAD program and this contractual effort has enabled the implementation of superplastic forming on the A-10 aircraft. In addition, more complex superplastic parts such as the environmental control door and speed brake door are currently being projected for the T-46 trainer. These parts have shown a reduction in costs through part and fastener reduction.

SECTION VI

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2. R. L. Rupp, et al: "Production Application of Weldbonding to the A-10," Final Report, Air Force Contract No. F33615-78-C-5121, Fairchild Republic Company, Farmingdale, New York, July 1981.

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4. A. J. Barnes, "Commercial Superplastic Aluminum Alloys - Opportunities and Challenges," presented at International Conference in Cranfield, England, July 1985.

5. A. J. Shakesheff, "The Effect of Superplastic Deformation on the Post Formed Mechanical Properties of the Commercially Produced Supral Alloys," presented at International Conference in Cranfield, England, July 1985.

6. Lt. R. Wilkinson and J. Tuss, "Quantitative Evaluation of Cavitation in Superplastic Formed Aluminum," Flight Dynamics Laboratory, (AFWAL/FIB).

APPENDIX A

TEST SPECIMEN CONFIGURATIONS

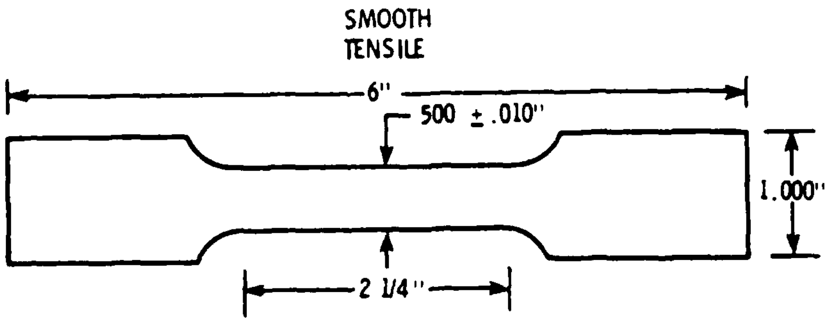


Figure A-1. Tensile Specimen $K_T = 1$

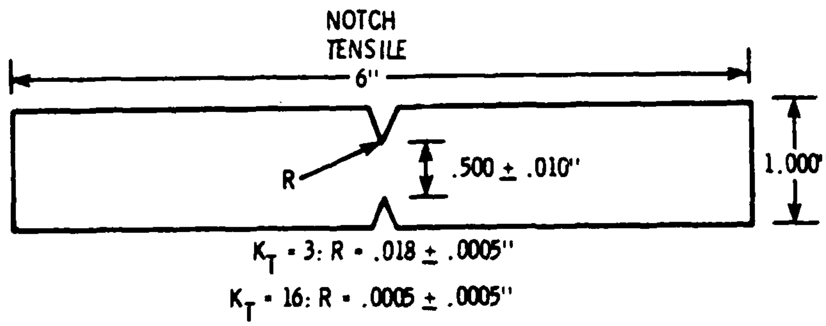


Figure A-2. Tensile Specimen $K_T = 3$, $K_T = 16$

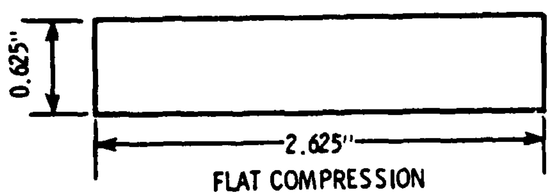


Figure A-3. Compression Specimen

Note: Thicknesses for all specimens ranged from 0.020-0.070". All dimensions are in inches.

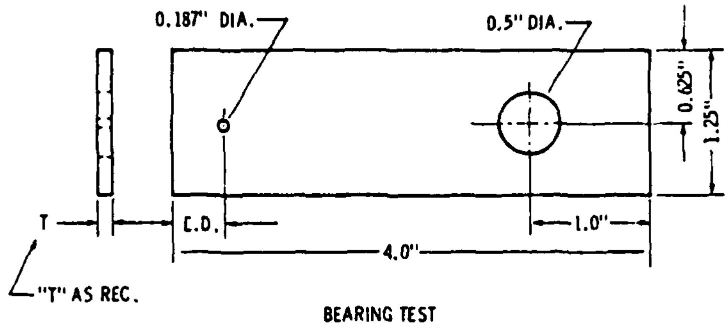


Figure A-4. Bearing Specimen e/D=1.5, e/D=2

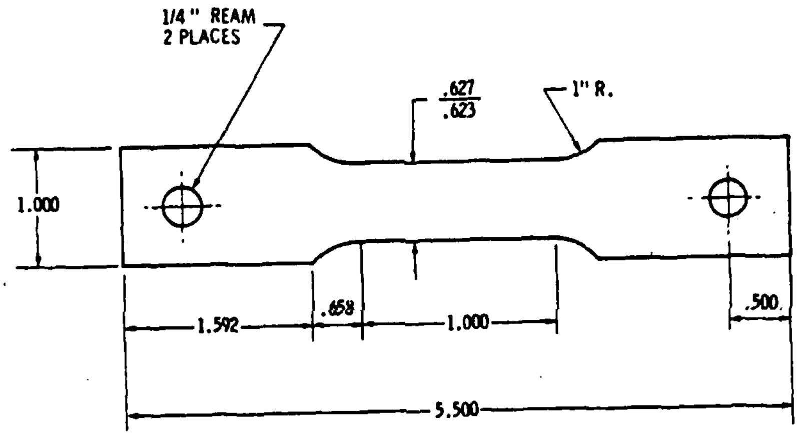


Figure A-5. Fatigue Specimen K_T=1

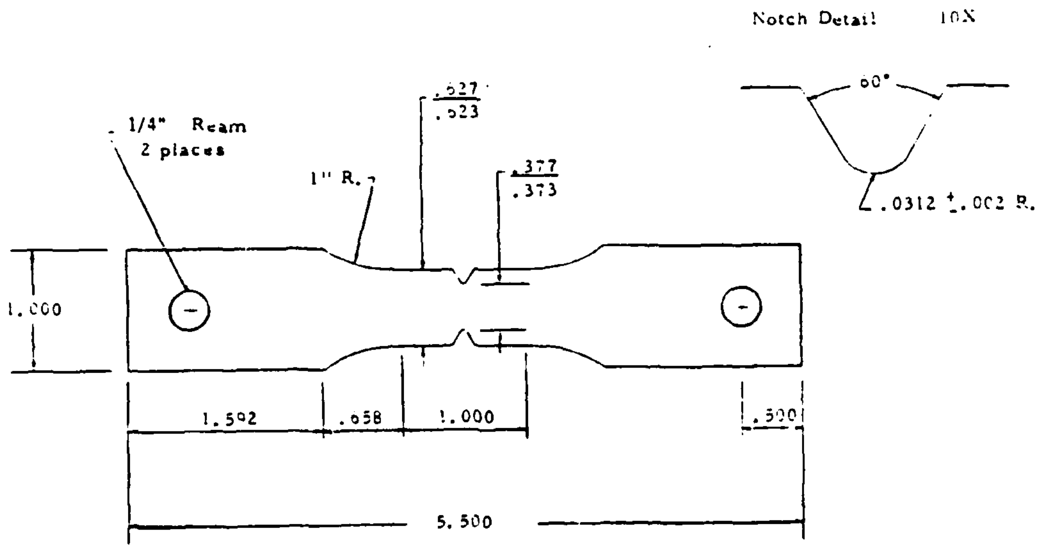


Figure A-6. Fatigue Specimen K_T=3

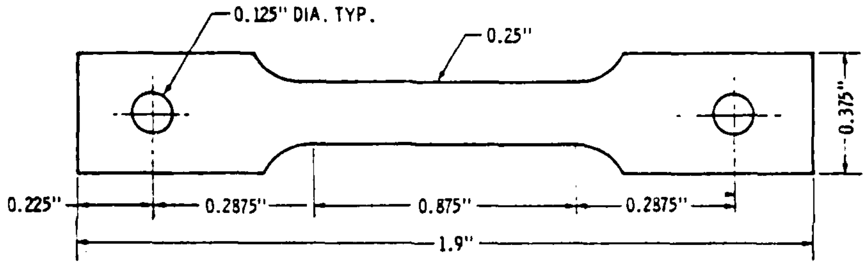


Figure A-7. Stress Corrosion Specimen

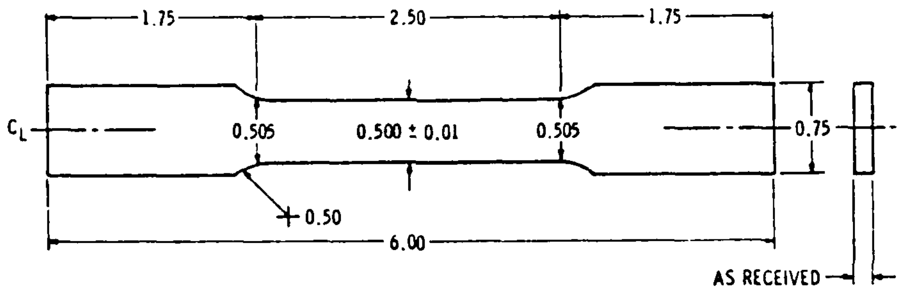


Figure A-8. Transverse Tensile Specimen (Fusion Welded)

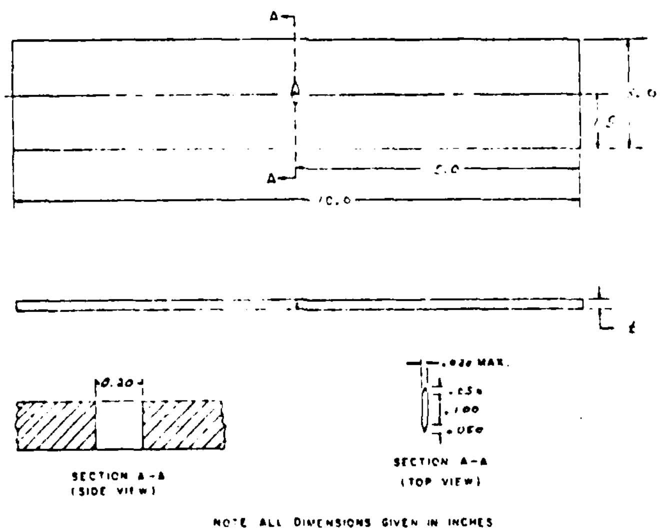


Figure A-9. Crack Propagation Specimen Used by AFWAL

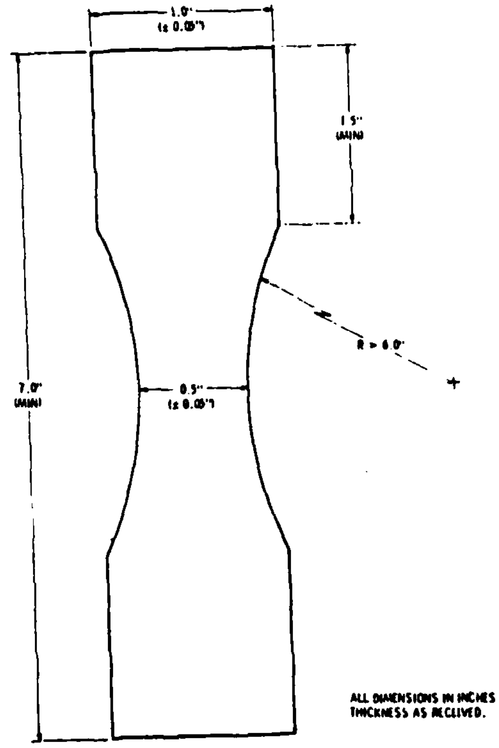


Figure A-10. Fatigue Specimen Used by AFWAL

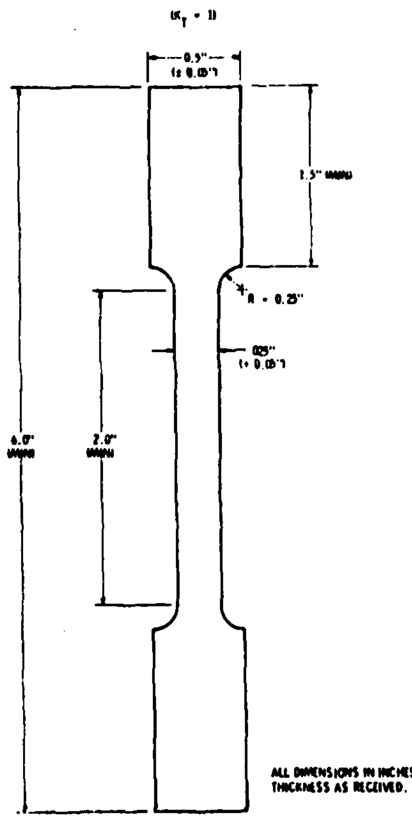
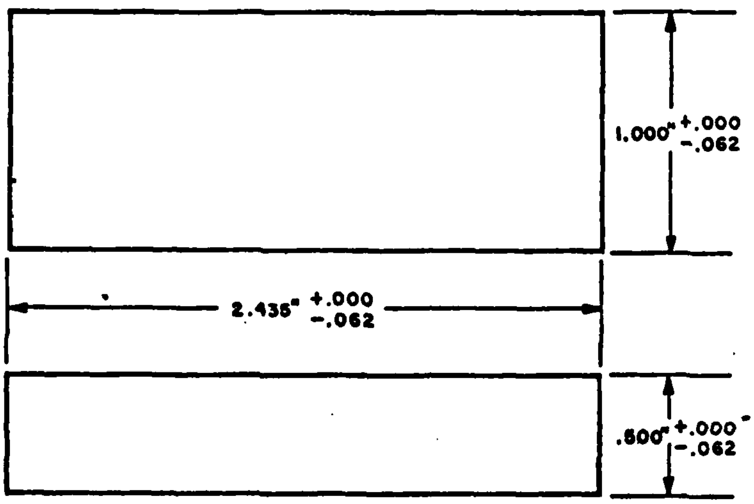


Figure A-11. Tensile Specimen Used by AFWAL

90° Impact Angle Specimen



ALL DIMENSIONS IN INCHES

*Actual specimen thickness is approximately 0.040 inch A lucite shim was added to obtain a thickness of 0.500 $^{+.000}_{-.062}$ inch

Figure A-12. Rain Erosion Specimen Used by AFWAL